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## ***Arc-Continent collision in Taiwan: New marine observations and tectonic evolution***

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### **ABSTRACT**

Marine observations offshore of Taiwan indicate intense deformation of the Luzon arc-forearc complex, with episodic eastward migration of the active deformation front across the complex. This active tectonic domain absorbs a significant amount of shortening between the Eurasia margin and the Philippine Sea Plate, which is moving towards N 310° E at about 8 cm/yr relative to Eurasia. Swath bathymetry and back-scattering data, together with seismic reflection and geopotential data obtained during the ACT (Active Collision in Taiwan) cruise onboard the R/V *L'Atalante*, showed major north to south changes in the tectonic style in both the indenting arc and the host margin.

Structural observations show that the forearc basement of the Luzon arc no longer exists north of 22°30'N. To the south, only a small part of the forearc domain may remain beneath the Huatung Ridge (rear portion of the former Manila trench oceanic accretionary wedge including forearc and intra-arc sequences) and rear of the thrust wedge. A tectonic model involving the progressive underthrusting of large slices of the forearc basement may account for the contrasting styles of deformation encountered from south to north across the collisional orogen and apparent missing of the forearc region. The progressive subduction of the continental margin of China induces: 1) to the south, major eastward backthrusting and shortening of the forearc domain between the former oceanic accretionary wedge and the Luzon Arc volcanic edifice, 2) to the north, accretion of parts of the arc domain to the collisional belt associated with westward thrusting, eastward backthrusting at the base of the slope and block rotation.

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## INTRODUCTION

Arc-continent collision and arc accretion along most continental margins mark the early episodes of mountain building. In the collision belts that can be studied in continental domains, the finite deformation exposed is very complex as a result of a long geologic history, generally involving numerous superimposed tectonic events. Thus, although ophiolite belts and slices of arcs, related to old oceanic suture zones, can be found in many mountain belts, it is often difficult to reconstruct the geodynamic setting and tectonic history prior to collision. To better understand the mechanics of mountain building, it is therefore fundamental to analyse the deformation processes acting currently in growing orogens.

The young Taiwan orogen has been the subject of study for many years, mainly on land (e.g., Biq, 1972; Chai, 1972; Jahn, 1972; Yen, 1973; Wu, 1978; Suppe, 1981; 1987; Barrier and Angelier, 1986; Ho, 1986; Lu and Hsü, 1992), but also offshore (e.g., Chen and Juang, 1986; Reed et al., 1992; Lundberg et al., 1992; Huang et al., 1992; 1997; Lallemand and Tsien, 1997). The geodynamic setting of the arc-continent collision is well defined and the general kinematics are well determined. The island itself represents the emerged part of a southward-propagating collisional orogen located between the Eurasian and Philippine Sea plates. South of the island, initial stages of the collision between the Luzon volcanic arc and the Chinese continental platform can be observed (Lundberg et al., 1997; Huang et al., 1997). To the north, the island of Taiwan corresponds to a mature stage of collision and arc accretion, resulting in a 4-km-high mountain belt. A portion of the evolving collision complex is under water to the east of the island (Fig. 1). This paper focuses on the active deformation occurring south and along the Coastal Range of Taiwan and its connection with the southern Ryukyu subduction zone (Lallemand et al., 1999).

Several geophysical cruises have been conducted in the offshore area of Taiwan since the early 1990s, providing multichannel and OBS (ocean-bottom seismograph) refraction seismic data (Liu et al., 1995; Wang et al., 1996; Lallemand et al., 1997a; Schnürle et al., 1998), seafloor mapping data (Reed et al., 1992; Lundberg et al., 1997; Liu et al., 1998), and gravity and magnetic data (e.g., Hsu et al., 1998). In 1996, EM12-Dual multibeam bathymetry, side-scan sonar imagery, six-channel seismic reflection data, and geopotential data were acquired during the 24-day-ACT (Active Collision in Taiwan) cruise of the R/V *L'Atalante* around southern and eastern Taiwan (Lallemand et al., 1997a). The southernmost lines were acquired during a transit cruise between Kaoshiung and Nouméa after the acquisition of the ACT data set. The survey covers most of the offshore area that was, and is currently, deforming owing to the subduction of the Chinese continental margin beneath the Luzon arc. These newly acquired data greatly contribute to setting limits on the timing and mode of deformation through detailed mapping of the offshore structural elements, including major active faults, ridges, morphology, drainage, and collisional basins.

We address in this study several important questions: How does the Philippine Sea plate and Luzon volcanic arc deform offshore during increasing subduction of the Chinese continental margin? What is the fate of the deformed Luzon Arc in advanced collisional stages (does it accrete to the Eurasian margin or does it disappear, subducting below the Philippine Sea plate)? Does the Central Range belong to the Chinese continental margin or to the Philippine Sea plate forearc domain (representing former parts of the China margin rifted apart during South China Sea opening)? How does exhumation of the metamorphic belt occur during convergence? Is the collisional process continuous, or does it occur in several distinct stages? Does the Longitudinal Valley, which was often considered as the on-land active plate boundary, extend offshore? What is the offshore equivalent of the Lichi mélange, presently described as a suture formation?

Data acquired during the ACT cruise build on a large body of previous work and provide for new interpretations of major structures and tectonic processes involved in the collision. As a result, an evolutionary model is proposed for the tectonic evolution of the Taiwan orogen for since 4 Ma.

## GENERAL SETTING

Two plates are involved in the complex tectonic setting that surrounds the Taiwan orogen, the Philippine Sea plate, and the Eurasian plate (Fig. 1). Northeast of the Taiwan area, the Philippine Sea plate is being subducted beneath the Ryukyu arc, which belongs to the Chinese continental margin. The Okinawa backarc basin is developed to the north of the Ryukyu arc (Letouzey and Kimura, 1985) and is associated with active extension and recent volcanic activity (e.g., Sibuet et al., 1999). South of the Taiwan island, the oceanic lithosphere of the South China Sea subducts beneath the Philippine Sea plate, inducing the volcanism of the Luzon arc. The relative motion between the Philippine Sea plate and the Eurasian plate has resulted in the progressive subduction of the Chinese continental margin and the development of the Taiwan mountain belt.

### *The Philippine Sea plate.*

Global kinematics indicate that the Philippine Sea plate is currently moving northwestward, with respect to the Eurasian plate (Seno, 1977; Seno et al., 1993). GPS (Global Positioning System) measurements on Lanyu Island over the 1990-1995 period provide a precise  $N306^\circ \pm 1^\circ$  azimuth for the convergence at a rate of 80-83 mm/yr relative to the Penghu Islands, which lie on the southern Chinese continental margin (Yu et al., 1997; Lallemand and Liu, 1998). The Philippine Sea plate near Taiwan consists of Eocene oceanic crust (Karig et al., 1975), and its western border is marked by the Luzon island arc. This arc and the associated Manila Trench are probably early Miocene in age, according to the oldest volcanic rocks (andesites) sampled in the Coastal Range of Taiwan by Juang and Bellon (1984).

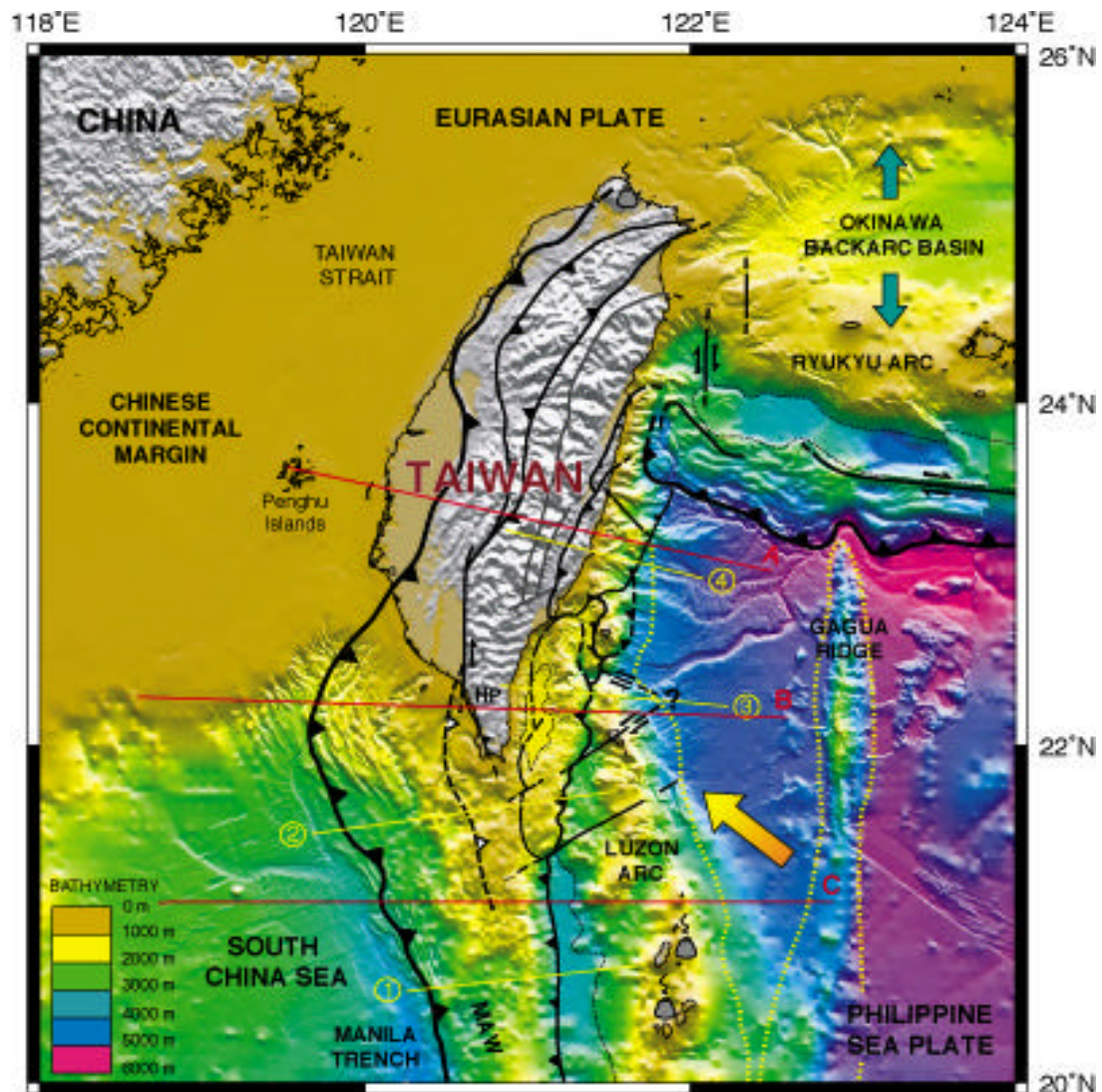


Figure 1. Geodynamic setting of the Taiwan orogen and location of the sections. The main tectonic units are shown on the shaded topographic view. MAW- Manila Accretionary Wedge, HP- Hengchun Peninsula.

The northernmost present-day activity of the arc is observed at the latitudes of the Batan Islands. Younger ages, as recent as 30 ka, were also found using K-Ar dating on Lutao and Hsiaolanyu (a small island located south of Lanyu) islands (Yang et al., 1996). The activity of the northern segment thus probably ceased during the Quaternary at the latitude of the islands of Lutao and Lanyu (Yang et al., 1996), or even farther north if younger volcanic rocks have been eroded from the uplifted Coastal Range (Richard et al., 1986).

A progressive increase in continental contamination of andesitic magmas correlates with progressively younger ages in Coastal Range volcanic rocks. This progression could

reflect the systematic increase through time of continentally derived sediment entering the Manila Trench (Dorsey, 1992), or simply the transition from oceanic to continental subduction, shortly before the cessation of island-arc magmatism.

#### *South China Sea, Manila Trench and Chinese Margin*

The South China Sea opened during Oligo-Miocene time (32 to 15 Ma). Magnetic lineations indicate that roughly north-northwest-south-southeast spreading migrated southwestward (Briais and Pautot, 1992). The fossil spreading ridge is currently subducting west of Luzon island (Pautot and Rangin, 1989). The oceanic lithosphere of the South

China Sea was subsequently subducted beneath the Philippine Sea plate along the Manila Trench in the early Miocene, as suggested by the Neogene age of associated volcanism along the Luzon Arc (Ho, 1986). The Manila accretionary wedge has developed between the two plates (Fig. 1) and is still growing today south of 21°20'N (Hayes and Lewis, 1984; Lewis and Hayes, 1983, 1984; 1989). North of 21°20'N, the wedge becomes incorporated in the arc-continent collision domain, involving progressively lower to middle Miocene slope and trench sediments (Reed et al., 1992). The southern tip of Taiwan Island, called the Hengchun Peninsula, extends offshore southward in the form of the Hengchun Ridge as far as 20°30'N (Fig. 1). This ridge is generally considered as the uplifted internal domain of the oceanic accretionary wedge currently undergoing the effects of the collision (Lundberg and Dorsey, 1990; Reed et al., 1992). A scenario for the tectonic evolution of the submarine accretionary wedge has been proposed by Huang et al. (1997) with the Kaoping slope west of the subduction wedge of the Hengchun Ridge representing the part of the prism associated with the active collision zone (e.g. Huang et al., 1997; Liu et al., 1997).

The continental shelf of the Eurasian plate bounds the South China Sea to the northwest. The shelf in the Taiwan Strait rarely exceeds 100 m depth and represents the flexural foreland basin of the Taiwan belt; up to 5 km of recent orogenic sediments has been deposited in former Cenozoic basins of the margin (e.g. Sibuet and Hsu, 1997). Indeed, in the early Tertiary, normal faulting resulted in the formation of Paleogene grabens along the Asian margin. Horst and graben structures, bounding these local basins filled with various thicknesses of sedimentary sequences, have played an important role in the development of the Taiwan thrust wedge (Suppe, 1988; Lu et al., 1998). The strata of these basins are currently exposed in the Western Foothills of Taiwan (Suppe, 1980; Davis et al. 1983), and some of the history and tectonic events of the arc-continent collision are registered in the young and nonmetamorphosed strata of the thrust wedge (Teng, 1991; Déramond et al., 1996). The transition between oceanic and continental crust in the Eurasian plate is marked approximately by the 2500 m isobath (Letouzey et al., 1988). Although being oriented approximately N 70°E to the southwest of Taiwan, the present trend of this boundary is not regular, which suggests that before collision, the margin could have presented a step-like geometry in the Taiwan area (Pelletier, 1985). If such a situation has occurred, the southward propagation of collision would not have been as continuous a process as is commonly believed.

### *The Taiwan Orogen*

The geologic setting of the Taiwan collision belt can be summarized as follows. The sedimentary cover of the Chinese continental margin (see Taiwan Strait in Fig. 1) was accreted in the northwestern part of the island, and it is still accreting in the southwestern part, against a backstop formed

by the pre-Tertiary rocks of the Central Range (e.g. Lu and Malavieille, 1994). Shallow marine sequences of the passive continental margin and foreland sequences constitute the deformed units of the Coastal Plain, Western foothills and Hsüehshan Range (Ho, 1982; 1988). During convergence, they were progressively accreted to the collision prism along a series of east-dipping thrusts.

The Central Range includes the Eocene and Miocene (but not Oligocene) metamorphic Backbone Range. The Lishan-Laonung-Hengchun Fault, west of the subduction wedge, is a high-angle west dipping reverse fault (Lee et al., 1997), which separates the western Backbone Range from the Eocene-Oligocene units of the Hsüehshan Range, both of them forming the slate belt (Ho, 1986; Angelier et al., 1990; Teng et al., 1991; Clark et al., 1993; Tillman and Byrne, 1995). The Western Foothills correspond to a fold-and-thrust belt affecting Oligo-Miocene strata overlain by a 4-km-thick sequence of Pliocene-Quaternary molasse (Lu and Hsü, 1992). This foreland thrust belt is inactive north of 24°N, but it is still growing south of this latitude as shown by GPS measurements (Yu et al., 1997). The Central Range is bounded to the east by the Longitudinal Valley, which separates the Central Range from the Coastal Range (i.e., northernmost segment of the Luzon volcanic arc). Deformation of the Philippine Sea plate lithosphere within the Coastal Range is suggested by the 50-km-thick seismogenic zone beneath the arc domain (Wu et al., 1997). The Coastal Range is still well coupled to the Philippine Sea plate, as attested to by the GPS velocities of  $63 \pm 9$  mm/yr in the direction of N314°  $\pm$  8°, except north of 23°40'N where rates dramatically drop to 8–43 mm/yr along the azimuths N292°–352° (Yu et al., 1997). About 8 cm/yr of plate convergence is taken up in the offshore area north of 24°N, whereas south of 24°N, the convergence is almost entirely distributed across the island, with 3 cm/yr accommodated in the Longitudinal Valley area (Angelier et al., 1997), and across the other thrusts of the Coastal Range shown in Figure 1 (Yu et al., 1997). Lundberg and Dorsey (1990) estimated the uplift rate of Quaternary marine terraces along the Coastal Range to be in excess of 6 mm/yr.

### MARINE OBSERVATIONS AND DATA ACQUISITION

The ACT cruise and the transit cruise between Kaoshiung and Nouméa aboard the R/V *L'Atalante* mapped an area of about 67 500 km<sup>2</sup> at 10 knots during 15 days with 100% bathymetric and backscattering coverage (Fig. 2A). Tracks were generally oriented parallel to the structures (Fig. 2B) in order to keep the swath width constant and because most of the previously acquired seismic lines were shot normal to the structural fabric. The ship is equipped with a SIMRAD EM12-Dual and EM950 (for depths shallower than 300 m) multibeam systems that enable swath mapping and side-scan imagery over a maximum 20-km-wide strip (151 simultaneous soundings) of seabed in a single pass. The side-scan imagery associated with EM12-Dual system gives detailed information on the acoustic reflectivity, which is related to



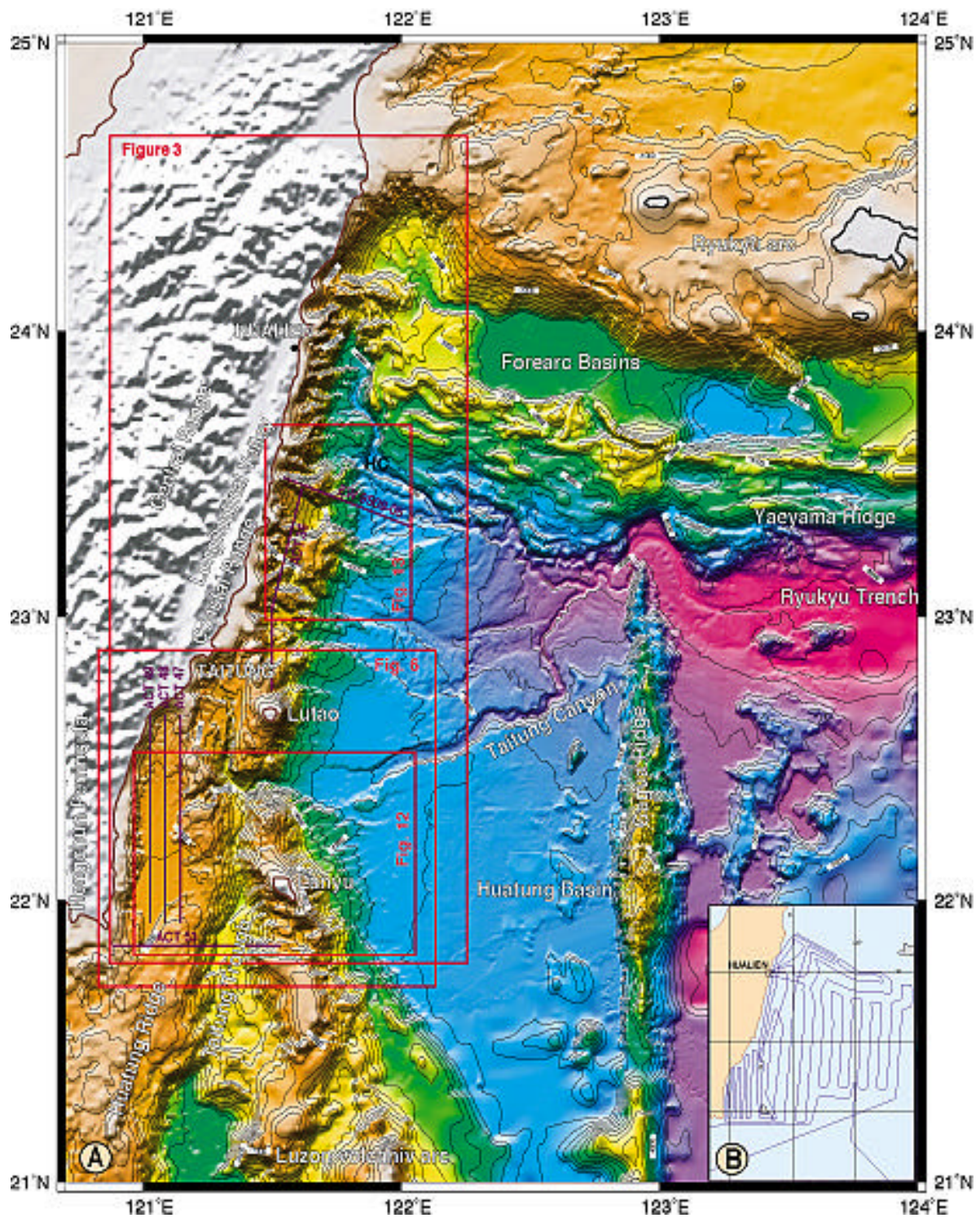


Figure 2. A) Bathymetry of the collision zone offshore east of Taiwan. Location of the main morphotectonic units and the seismic lines described in the paper are shown. HC- Hualien Canyon. B) Ship tracks.

small-scale bathymetric features and to variations in the nature of the seafloor. Subbottom (3.5 kHz) and reflection seismic profiling and magnetic and gravity data were also recorded along the 20-km-spaced ship-tracks (for great depths) and along more closely spaced tracks at shallower depths. Six-channel streamer was deployed with two 75 cubic inch GI guns at a pressure of 160 bars. The guns were fired in harmonic mode to generate a source signature centered on 20 Hz to enhance subbottom penetration of energy. Shot intervals were ~50 m. Seismic data were processed with ProMAX software to obtain post-stack time-migrated profiles.

### FROM INCIPIENT TO MATURE ARC-CONTINENT COLLISION OFFSHORE EAST TAIWAN.

Arc-Continent collision is classically considered to be exemplified by the subduction of the continental margin of China under the Luzon island arc (Fig. 1). The transition from oceanic to continental subduction along the Manila Trench occurs near 22°N (Reed et al., 1992), but the impact on deformation of this major change in the nature of the two plates is observed as far south as 21°N.

#### *Main structural elements*

The main tectonic features are defined on the tectonic maps (Figs. 1 and 3) and shaded bathymetric map (Fig. 4). Two structural domains constitutes the collisional area :

A southern domain is composed by four morphotectonic structures that characterize the domain of incipient collision : (1) the Southern Longitudinal Trough south of the on-land Longitudinal Valley, (2) the elongated Huatung Ridge forming the eastward dam of the Southern Longitudinal Trough, (3) the Taitung Trough, marked by a sinuous V-shaped valley, and (4) the Luzon volcanic arc including the islands of Lanyu and Lutaot.

A northern domain represents the area of well-developed collision; it includes (1) the Coastal Range and its offshore eastern flank, (2) the western termination of the Ryukyu accretionary wedge, and (3) the complex area which marks the junction between the collision zone and the Ryukyu Trench in which the Heping Basin has developed.

The boundary between the two structural domains is characterized by a transfer zone of deformation that accommodates their different mechanical evolution. Figure 3 summarizes the major tectonic features observed and the kinematics of the main units given by the GPS data of Yu et al. (1997).

Four east-west geologic cross sections (Fig. 5; drawn with no vertical exaggeration; locations in Fig. 1) are presented; they are based on the analysis of data from the ACT cruise. These sections illustrate the major structural changes occurring from the south to the north, because of the increasing involvement of the Chinese continental margin in the subduction and collision. The interpretation of the structure at depth proposed for the four sections and the deformation mechanisms involved are explained and discussed subsequently.

Section 1, based on interpretations in Reed et al., (1992), is located around 21°N and shows the typical geometry of the Manila accretionary wedge, with backthrusting at the rear that controls the development of the North Luzon Trough forearc basin. North of 21°20'N, the size, morphology and structure of the accretionary wedge changes significantly owing to the first effects of the collision. The forearc basin is shortened in between the rear of the wedge and the volcanic edifice of the arc.

Section 2, redrawn from Reed et al. (1992), shows the structure of the wedge. Three main morphotectonic units appear: (1) a lower-slope wedge with a very low slope, (2) an uplifted domain of the wedge (the Hengchun ridge) bounded by a slope break and characterized by a steeply dipping upper-slope, (3) a smaller ridge, composed by deformed strata of part of the former wedge and forearc sedimentary deposits, separated from the rear of the wedge by a narrow north-south-oriented valley (see also in Fig. 1). Reed et al. (1992) suggested significant shortening of the central domain of the wedge, with out-of-sequence thrusting at the boundary between upper and lower slopes and major backthrusting in the forearc domain. North of 22°N, the Hengchun Peninsula represents the emerged continuation of the submarine Hengchun Ridge. At this latitude, a large part of the slope sediments from the continental margin is involved in the accretionary wedge.

Section 3 shows the development of a Quaternary collisional basin (the Southern Longitudinal Trough) between the eastern flank of the Hengchun Peninsula and the Huatung Ridge overthrusting onto the Luzon arc (Lundberg and Dorsey, 1988) (Fig. 1). Along this section again, major shortening occurs today in the forearc domain (Lundberg and Dorsey, 1997). The Southern Longitudinal Trough is partly filled with sediments coming from the erosion of the emerged Taiwan mountains (Lundberg and Dorsey, 1988). It is not the northern equivalent of the North Luzon Trough forearc basin, which is filled with arc-derived volcanoclastic sedimentary deposits and which ends south of the Huatung Ridge at about 21°20'N. From 22°40'N to about 24°N, the collision is completed and the forearc domain is drastically reduced.

Section 4 shows the active westward thrusting of the Coastal Range on the formerly exhumed metamorphic rocks of the Central Range. The on-land Coastal Range and its offshore slope continuation are composed of offscraped parts of the former volcanic arc edifice, intra-arc basins, and strongly deformed forearc strata. This tectonic unit may be decoupled from the Philippine Sea plate oceanic basement by an west dipping thrust located close to the base of the slope (Fig. 1).

#### *Deformation in the southern structural domain*

**The Southern Longitudinal Trough and surroundings.** The Southern Longitudinal Trough (Fig. 4) is a proximal orogenic basin developed in a forearc position (e.g., Lundberg and Dorsey, 1988; Lundberg et al., 1997; Fuh et al., 1997). The trough is elongated in a north-south direction

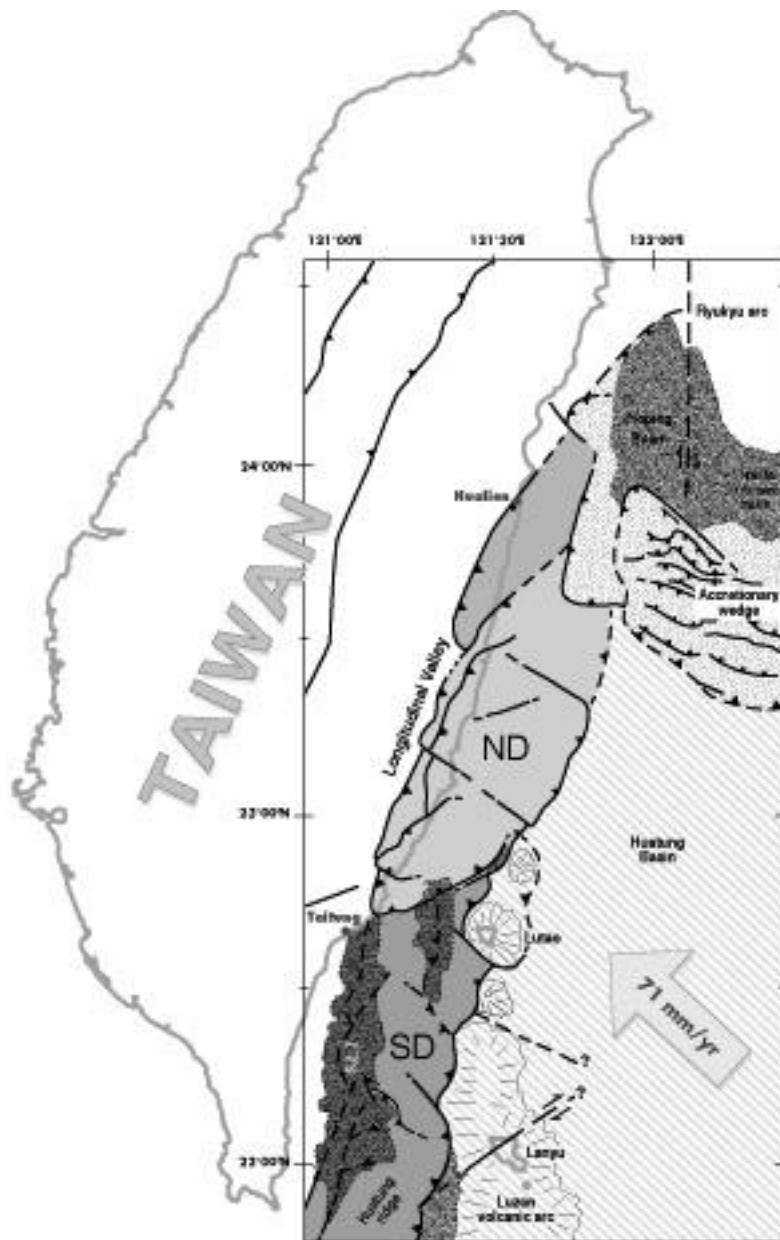


Figure 3. Schematic tectonic map of the study area showing the kinematics of the main tectonic units (GPS data after Yu et al. [1997]). The 95% confidence ellipse is shown at the tip of each velocity vector. ND- northern tectonic Domain, SD- southern tectonic Domain.

Between 21°50'N and 22°40'N. Its shape is complex ; it is about 90 km long, 15 km wide and it narrows toward the south. The seafloor of the trough deepens from 800 m to the north to 1300 m to the south. It is bounded to the west by the 10°-east-dipping structural slope of the Hengchun Peninsula and to the east, by an antiformal narrow ridge which extends westward from the Huatung Ridge near 22°05'N, about 600 m higher than the seafloor of the Southern Longitudinal Trough.

Today, sediments are mainly supplied from the sub-aerial peninsula through numerous east-trending gullies. Most of the sediments coming from the Central Range through the Longitudinal Valley are dumped into the Taitung Canyon (see north-looking perspective view in Fig. 6), but some of them are collected by the tributaries of another canyon, which begins in the northern part of the Southern Longitudinal Trough, turns sharply east, meanders across the Huatung Ridge near latitude 22°20'N, and finally flows into



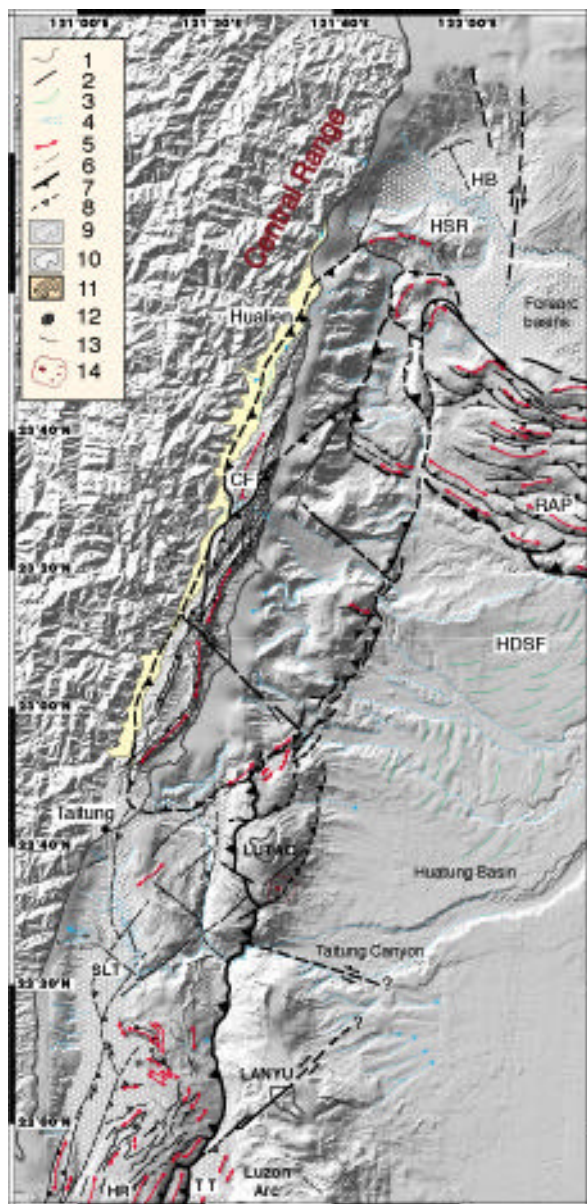


Figure 4. Structural map of the study area offshore Taiwan. Geological features are drawn on the bathymetry (shaded view, illumination from N310°E). Symbols and patterns: 1 - geologic boundary, 2 - fault, 3 - large scale mud waves, 4 - drainage, 5 - fold axis, 6 - minor fault, 7 - thrust (teeth on upper plate), 8 - inactive thrust (teeth on upper plate), 9 - recent collisional basin, 10 - Quaternary deposits of the Longitudinal Valley, 11 - volcanic rocks of the Coastal Range, 12 - mud volcano, 13 - normal fault, 14 - mass wasting. SLT- Southern Longitudinal Trough, HR- Huatung Ridge, TT- Taitung Trough, CF- Chimei Fault, HSR- Hsingsen Ridge, HB- Hoping Basin, HDSF- Hualien Deep-Sea Fan, RAP- Ryukyu Accretionary Prism.

the Taitung Canyon position (Fig. 4) (Lundberg and Dorsey, 1988; Lundberg et al., 1997). The Central Range source for Holocene orogenic sediments was confirmed by box coring into the basins conducted during two cruises of the R/V *Ocean Researcher I* in 1988 and 1989 (Huang et al., 1992). Samples cored in the southern part of the Southern Longitudinal Trough consisted of hemipelagic mud with slate chips, and samples cored at the head of the Taitung Canyon contained angular metamorphic detritus. The Taitung Canyon crosses the Luzon Arc and the Huatung Basin, reaches the Ryukyu Trench and finally emerges at a distal fan east of the Gagua Ridge (see the detailed study by Schnürle et al., 1998). The flat floor of the Taitung Canyon is strongly reflective in backscattering images, suggesting the presence of coarse sediments or gravels (Fig. 7). The east-trending gullies on the western border of the Southern Longitudinal Trough are also reflective, whereas the braided channels on the floor of the Southern Longitudinal Trough are much less reflective. This difference could be interpreted as marking a slope break at the heads of the gullies, which provide sediments to the channels, or may be caused by the change in slope steepness.

Migrated six-channel, seismic reflection profiles across the Southern Longitudinal Trough, acquired during the MW9006 cruise of the R/V *Moana Wave* in 1990, reveal that much of the basin is filled by growth strata, which record relative uplift of the Huatung Ridge, forming the dam of this basin (Lundberg et al., 1992; 1997). Uppermost strata are nearly flat lying, but with increasing depth, the strata dip westward, documenting progressive tilting, probably resulting from uplift of the eastern part of the basin. Gently west-dipping thrusts have been imaged from east-west seismic lines (Lundberg et al., 1997).

Figures 8, 9 and 10, represent time-migrated, six-channel seismic lines ACT 49, ACT 48, and ACT 47, respectively, recorded along the Southern Longitudinal Trough (see Fig. 2 for location). These three parallel north-south lines illustrate the complex structure of the trough. The line ACT 49 (Fig. 8) follows the western part of the basin. The upper series of the basin are relatively flat, onlapping the Huatung Ridge to the south, whereas at depth, the lower strata overlying an irregular basement are gently deformed. An unconformity may separate the two sedimentary sequences. On the line ACT 48 (Fig. 9), located on the median part of the trough, the thickness of the younger strata above the unconformity remains the same, but the underlying sequences are thicker and more deformed than those from the western side of the trough. The lower sequences of the basin appear to be contained in three minor troughs: a southern one, which shows folding between two basement structures, a relatively undeformed middle trough dipping north, and a northern trough, with a gentle syncline structure, separated from the previous basin by a deformed zone of uplifted basement. ACT 47 line (Fig. 10) crosses the eastern part of the Southern Longitudinal Trough and shows that the undeformed sequences in the upper part of the basin exist only in the southern trough (see also Fig. 4). These sequences lie unconformably on top of older, folded and faulted sequences



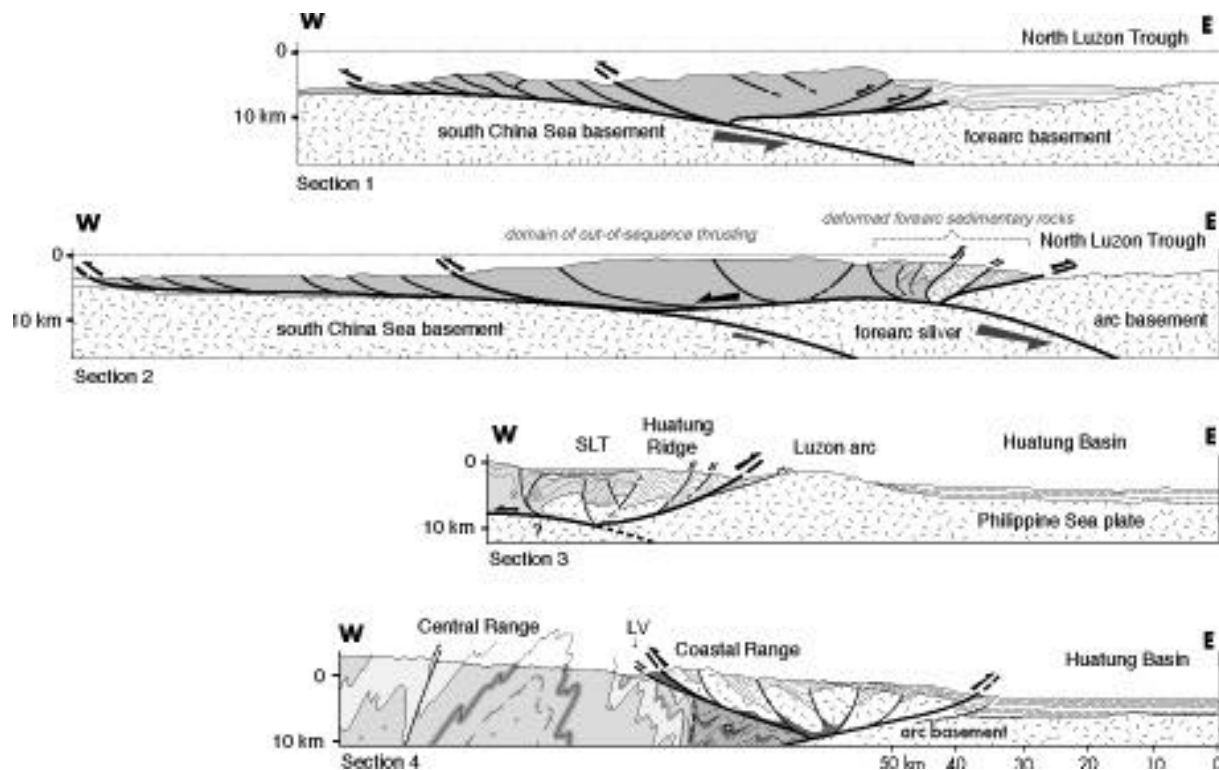


Figure 5. Geologic cross sections (all are at the same scale with no vertical exaggeration). Sections 1 and 2 are based on Reed et al. (1992). See location of sections in Figure 1.

of the former trough. In the northern domain, the lower sequences have undergone complex deformation involving thrusting.

Our observations suggest that the Southern Longitudinal Trough was developed in a complex tectonic setting during at least two different stages. First, the trough was represented by an early stage of basin development in an area of active shortening. The shape of the thrusts leads us to interpret them as positive flower structures, and the orientation of the folds oblique to the north trend of the trough strongly suggest that deformation occurred between two growing ridges in a domain of sinistral transpressional tectonics, probably as a result of the oblique convergence of the Philippine Sea plate. A more recent second stage occurred during which the sediments were deposited unconformably on top of the earlier-deformed strata. This second stage occurred after the main region of deformation migrated eastward toward the Huatung Ridge.

After correlation of the strata on both east-west and north-south lines at intersecting points, we observed that the "nearly flat-lying" uppermost strata along east-west transects are gently folded along axes oblique to the north trend of the basin (Fig. 6); the strata locally dip about 10°. These units

probably represent the younger generation of growth strata recording recent deformation.

The structural analysis shows that the present collisional basin is tilted to the west because of the growing Huatung Ridge on its eastern border, but it is also deformed by transverse structures. Such deformations are likely due to the local effects of the oblique indentation of the growing Huatung Ridge by the irregular western slope of the Luzon island arc.

As the Longitudinal Valley is currently characterized by east-dipping thrusting (e.g. Angelier et al., 1997), we expected before the cruise to find the same active deformation in the Southern Longitudinal Trough. Despite the morphological continuity between the Longitudinal Valley on land and the offshore trough, the most surprising observation was the absence of any sign that could reveal the activity of east-dipping reverse faults in the Southern Longitudinal Trough (Lundberg et al., 1997). To the contrary, we observe that: (1) the eastern flank of the Hengchun Peninsula is continuous from onshore to offshore (10° E-dipping structural slope), (2) the orogenic north-south-elongated sedimentary basin follows the N30°E-trending Longitudinal Valley basin but is 1000 m deeper south of Taitung, and (3) the Southern Longitudinal Trough is controlled by the east-verging anti

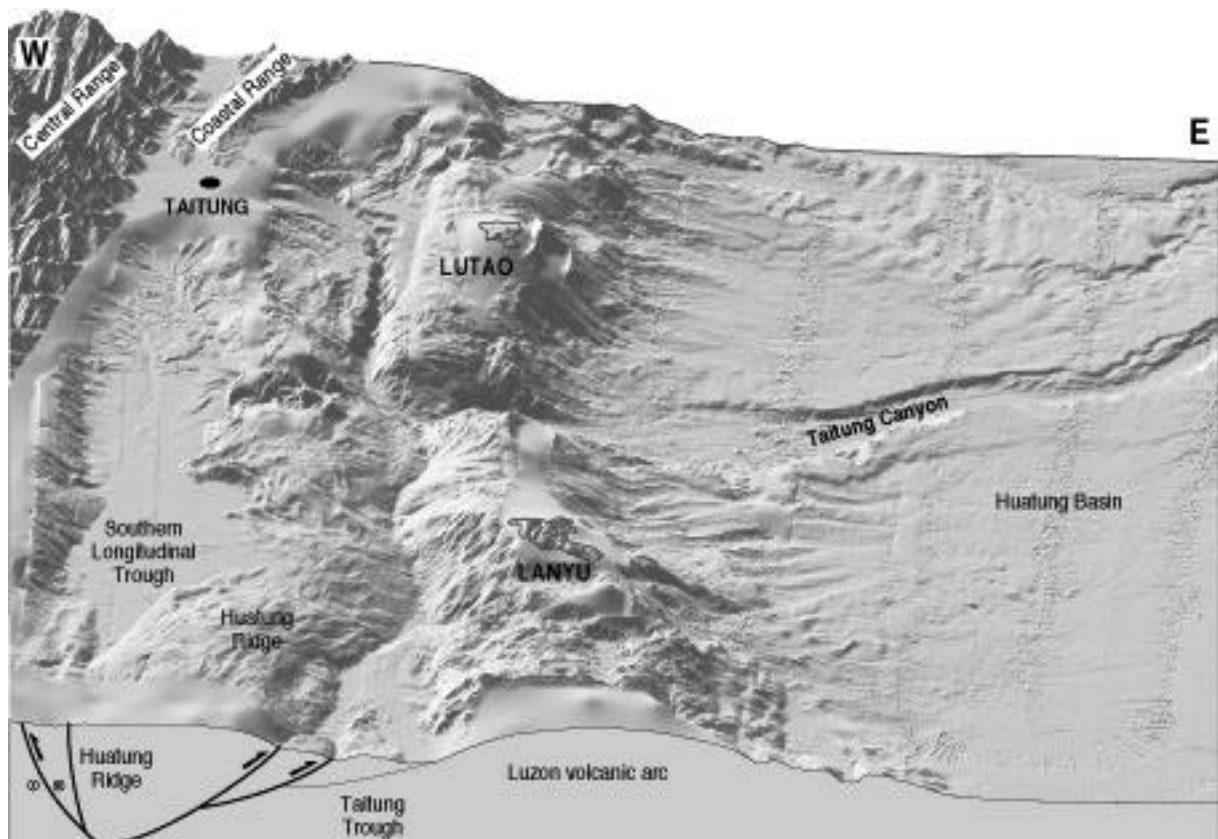


Figure 6. Shaded hill relief of the southeastern area showing front-view cross section and the main morphostructural features (perspective view looking north).

formal structures of the Huatung Ridge, not by equivalents of the east-dipping thrusts of the Coastal Range.

**The Huatung Ridge.** The preceding observations imply that at least the upper layers of the Huatung Ridge consist of growing orogenic strata of the Southern Longitudinal Trough. Huang et al. (1992) noticed that, despite the morphological continuity between the Coastal Range and the Huatung Ridge, the ridge exhibits negative values of both free-air and magnetic anomalies (Liu et al., 1992). They thus concluded that it consists mainly of a sedimentary mass. Reed et al. (1992) suggested that the deformed forearc basin forms an important constituent of the Huatung Ridge. Samples cored on the Huatung Ridge revealed sandstone and mudstone subangular cemented blocks within a sheared mudstone matrix, similar to the onshore "Lichi mélange" (see the geological map of eastern Coastal Range [Huang et al., 1993]). Part of the Huatung Ridge could be the offshore equivalent of the Lichi mélange which is interpreted as an olistostromal syntectonic mélange formed during the arc-

continent collision (e.g., Page and Suppe, 1981; Huang et al., 1992).

The ridge is not continuous. North of  $22^{\circ}02'N$ , it trends north, is 20 to 30 km wide, and reaches 600 m in relief with respect to the adjacent Southern Longitudinal Trough floor (Fig. 4). South of  $22^{\circ}02'N$ , it trends  $N20^{\circ}E$  and is 25 km wide, and its top is 500 m higher than the adjacent basin floor. The northern part shows a complex seafloor reflectivity whereas the top of the southern part is strongly reflective (Fig. 7), suggesting the presence of outcrops of coarse sediments or well-lithified sediments.

The moderately reflective eastern flank of the Huatung Ridge is steeper and higher than the western flank. Its height reaches a water depth of 1200 m at  $22^{\circ}10'N$  and increases to 2400 m to the north and to 2100 m to the south. The average slope is  $10^{\circ}$  but reaches  $20^{\circ}$  in the northern part of the ridge (Fig. 4). South of the study area, the east-west ACT 53 seismic profile (Fig. 11) confirms that the ridge is thrusting over the Taitung Trough termination. In fact, such backthrusting was formerly observed during the POP2 cruise onboard the R/V *Jean Charcot* in 1984 (J.F. Stéphan, personal

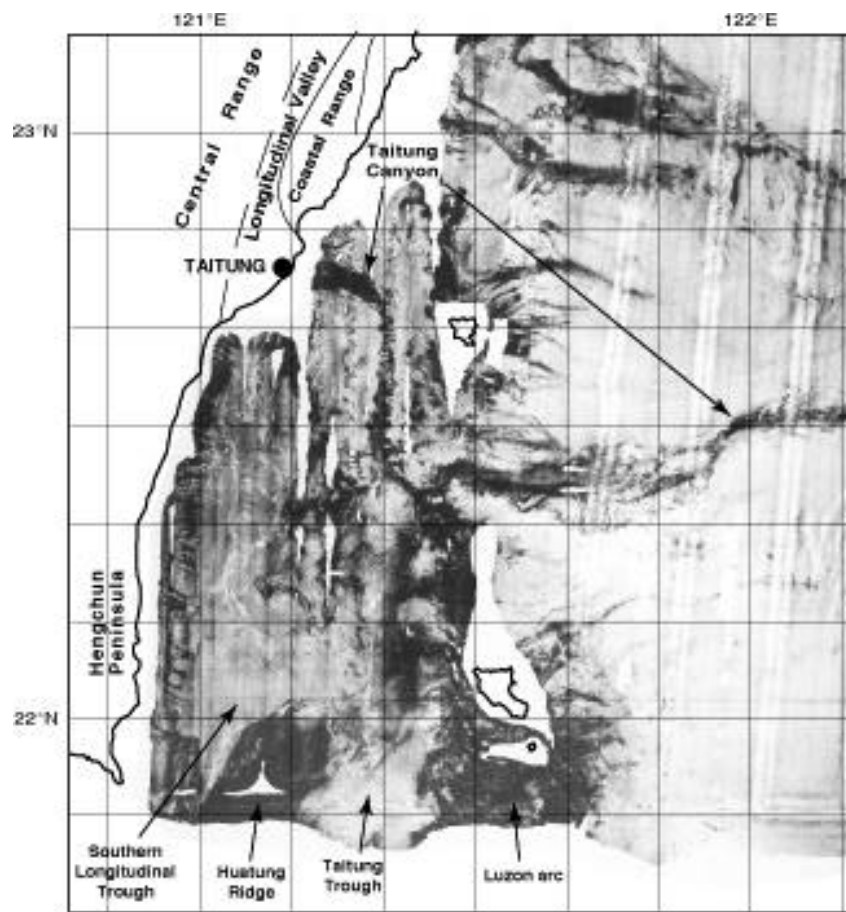


Figure 7. Side-scan sonar imagery of the study area. Note the strong reflectivity (black) of the Taitung Canyon floor, top of Huatung Ridge and Luzon volcanic arc and the low reflectivity of the small channels of the Southern Longitudinal Trough and of the southeastern steep slope of the Huatung Ridge.

communication, 1996) (Pelletier, 1985) and later during the R/V *Moana Wave* MW9006 cruise in 1990 (Lundberg et al., 1997).

South of  $21^{\circ}30'N$ , the Huatung Ridge disappears. The Hengchun Ridge directly dams the arc sediments in the North Luzon Trough, which is the forearc basin associated with the Manila Trench subduction zone. Backthrusting at the rear of the wedge controls the development of the forearc basin (section 1 in Fig. 5) (Reed et al., 1992; see also Larroque et al., 1995, for the mechanisms of basin development). At  $22^{\circ}N$ , the Taitung Trough narrows drastically and extends northward into a V-shaped valley. The seafloor in the trough shallows symmetrically northward and southward from a depth of 3000 m toward a pass, 2000 m deep, at  $22^{\circ}10'N$  (Figs. 1 and 4). This morphology, together with the westward tilting of the overlying strata of the Southern Longitudinal Trough, shows that the Huatung Ridge is thrusting over the Luzon volcanic arc at least between  $22^{\circ}N$  and  $22^{\circ}25'N$ .

The general map of figure 1 and the ACT 99 line acquired during the transit between eastern and western studied domains shows the same backthrusting of the Huatung Ridge more to the south, down to  $21^{\circ}20'N$  (also described in Lund-

berg et al. [1997]). North of  $22^{\circ}25'N$ , the Huatung Ridge widens and is cut by the head of the Taitung Canyon, which extends southward to  $22^{\circ}25'N$  where it turns east and crosses the volcanic edifice to join the Huatung Basin to the east. The north-trending part of the canyon cuts into the flat-lying sediments of a recent basin, which previously filled the narrow trough developed between the Huatung Ridge and the volcanic edifice of Luta Island. The thick sequence of sediments in this basin remain tectonically undisturbed as revealed by east-west reflection seismic lines (Huang et al., 1992) and north-south seismic profiles (this study). At about  $22^{\circ}22'N$ , a sinuous canyon incises the Huatung Ridge and joins the east-trending segment of the Taitung Canyon (Fig. 12).

These last observations suggest that early in the history of the Huatung Ridge formation, most of the sediments coming from the Central Range, via the Longitudinal Valley and the former paleo-Taitung Canyon, filled the developing Southern Longitudinal Trough and then crossed the ridge and the volcanic arc to be deposited in the Huatung Basin. It seems that because of the rapid growth of the Huatung Ridge and the increasing thrusting to the east over the arc, the

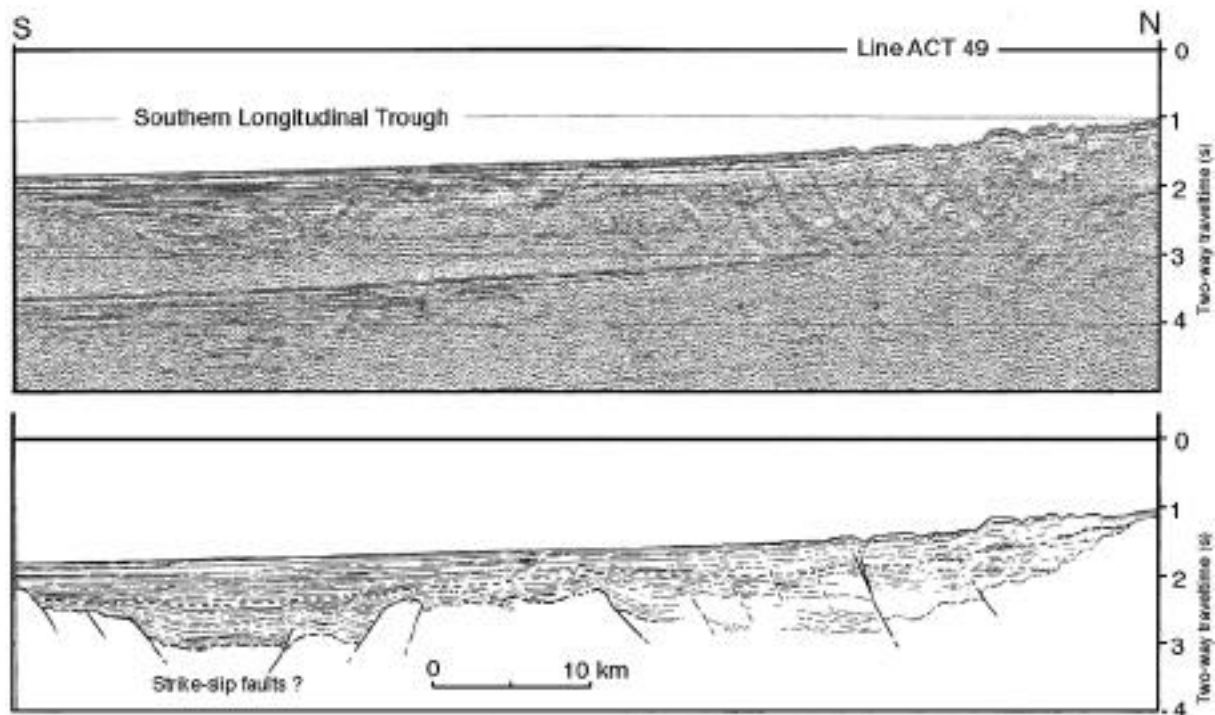


Figure 8. North-south seismic profile across the eastern part of the Southern Longitudinal Trough. (A) Migrated six-channel profile, (B) Line drawing showing the main geologic features.

paleo-Taitung Canyon was progressively abandoned or became less efficient. Its new bed was uplifted, resulting in the north-south-oriented canyon currently crossing the Taitung Basin and deeply incising the strata.

The ACT data show that the shortening between the Luzon Arc (islands of Luta and Lanyu) and the Hengchun Peninsula of Taiwan is mainly absorbed along the west-dipping thrust beneath the Huatung Ridge; however, the shortening is partially accommodated by folding and thrusting within the ridge, as previously mentioned in Lundberg et al. (1997). South of Taitung, the difference between GPS data obtained on the arc islands (Luta and Lanyu) and on east coast of the Hengchun Peninsula confirms that about 4 cm/yr (half of the total convergence) (Yu et al., 1997) is accommodated offshore.

#### ***Deformation of the northern structural domain***

***Offshore deformation east of the Coastal Range.*** On land, two main tectonic units are characterized by active deformation. The boundary between the southern and northern unit is marked by the southeast-dipping Chimei Fault (Fig. 4).

Offshore, east of the Coastal Range, the slope is actively deforming. Minor northwest-trending strike-slip faults

(probably left lateral), west-dipping thrusts and north-northeast-trending folds characterize the deformation (Figs. 13 and 14). About 1.7 cm/yr should be accommodated there as indicated by published geodetic data (Yu et al., 1997), probably mainly along thrust faults marked by the steep scarps cutting the range to the east. A seafloor vertical offset of about 500 m is observed downstream of the flat-floored Chimei Canyon (see the perspective shaded view Fig. 13). It has been interpreted from the seismic line EW 9509-05 (Fig. 14) (Liu et al., 1998), slightly oblique to the scarp, as caused by west-northwest-dipping reverse faults. North-south ACT seismic profiles show that most of the offshore slope is covered by sediments that could be derived from the Coastal Range and deposited in former intra-arc or forearc basins. The strata are locally folded and faulted, showing that the whole unit has undergone shortening.

The submarine Hualien Canyon flows roughly north-south through the Ryukyu accretionary wedge and follows the trench where it runs eastward joining the Taitung Canyon close to the Gagau Ridge (Fig. 2). The Chimei Canyon provides a conduit for the sediments coming from the growing Central Range through a unique valley crossing the Coastal Range. The submarine extension of the canyon extends across a large sedimentary fan in the northwest corner of the Huatung Basin and joins the Hualien Canyon at the



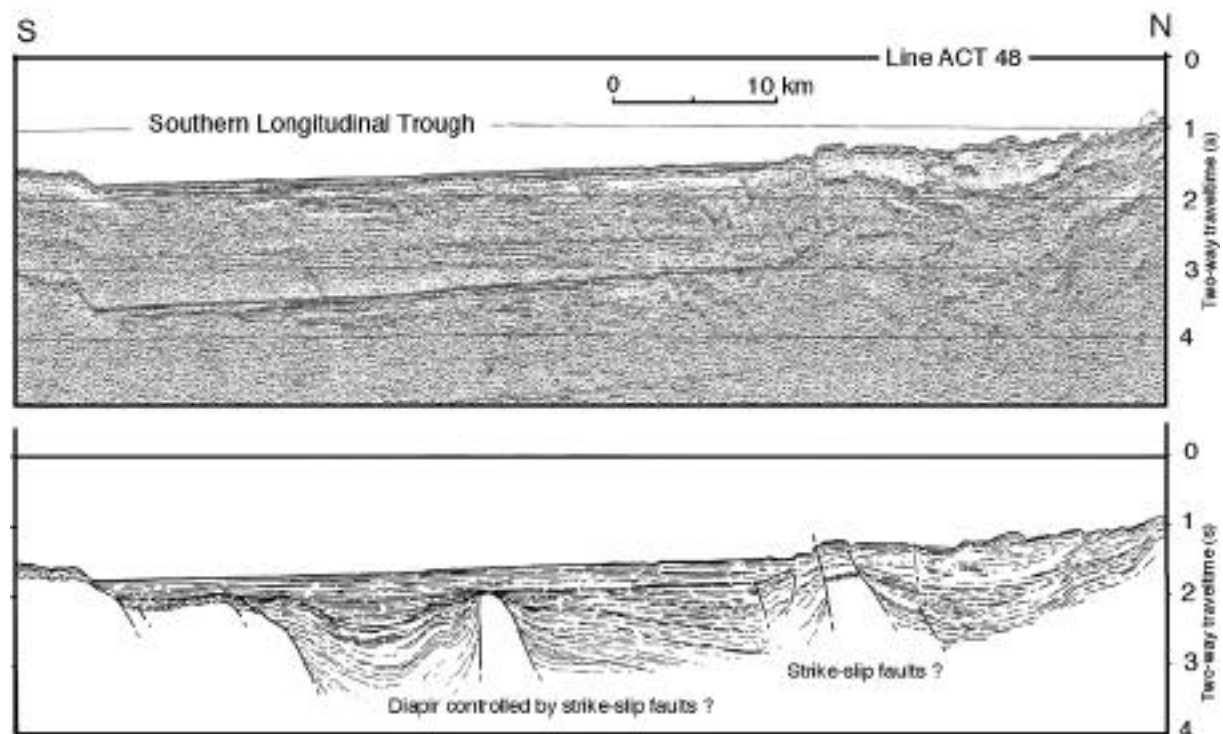


Figure 9. North-south seismic profile across the central part of the Southern Longitudinal Trough. (A) Migrated six-channel profile. (B) Line drawing showing the main geologic features.

trench. Several other minor canyons coming from the eastern flank of the Coastal Range mountains flow downslope toward the Huatung Basin (Fig. 4).

From Taitung to 23°40'N, 3 cm/yr are taken up along the east-dipping thrusts of the Longitudinal Valley, and 1.7 cm/yr of shortening occurs offshore, through west-dipping thrusts (calculated from geodetic data [Yu et al., 1997]).

From 23°30'N to 24°10'N, the area of Hualien is actively deformed, as indicated by the intense seismicity, geodetic data, and the steepness of the eastern flank of the range. Accretion of the northernmost part of the Luzon arc lithosphere may thus be achieved at these latitudes. The small northern Coastal Range tectonic unit terminates northward against the Hsincheng Ridge, an uplifting sedimentary mass, which is supposed to be a remnant part of the inner domains of the Ryukyu accretionary prism. Lallemand et al. (1999) have studied the area immediately north of the Coastal Range. They have interpreted the Hsincheng Ridge (Fig. 4) as the last possible surface indication of the presence of the Luzon arc to the north, suggesting that (1) the arc never extended northward and (2) only the oceanic crust of the Philippine Sea plate subducts beneath northern Taiwan.

North of the Longitudinal Valley, the offshore steep slope of the eastern flank of the Central Range suggests faulting between the arc domain (the trough filled by the

Hoping Basin) and the Central Range (Fig. 2). This area corresponds to the place where drastic changes in kinematics are suggested by GPS data (Lallemand and Liu, 1998). Indeed, instead of westward convergence, the displacement vectors show that the northern Coastal Range domain is not moving relative to the Chinese continental margin. In this area, the eastern boundary of the backthrust front is not easy to recognize because the Hualien Canyon deeply incises the materials of both the forearc and the accretionary wedge. Bathymetric and morphologic evidence suggest that large volumes of sediments were previously deposited in this area and are currently being removed by erosion. The wide deep-sea fan, which was formed early at the boundary between the frontal slope of the wedge and the submarine Coastal Range, is also deeply eroded. Wide, east-trending canyons (Chimei Canyon, for example) also cut the east-dipping slope of the island, developing deep-sea fans of gravelly sediments and transporting detritus far toward the east in the Ryukyu Trench (Fig. 13). These observations suggest that the general tectonic and sedimentologic environment has changed recently.

**Major tectonic changes at the latitude of Taitung.** An important tectonic boundary forms the southern limit of the Coastal Range and its offshore continuation (Fig. 4). A northeast-trending, curved fault zone characterized by a

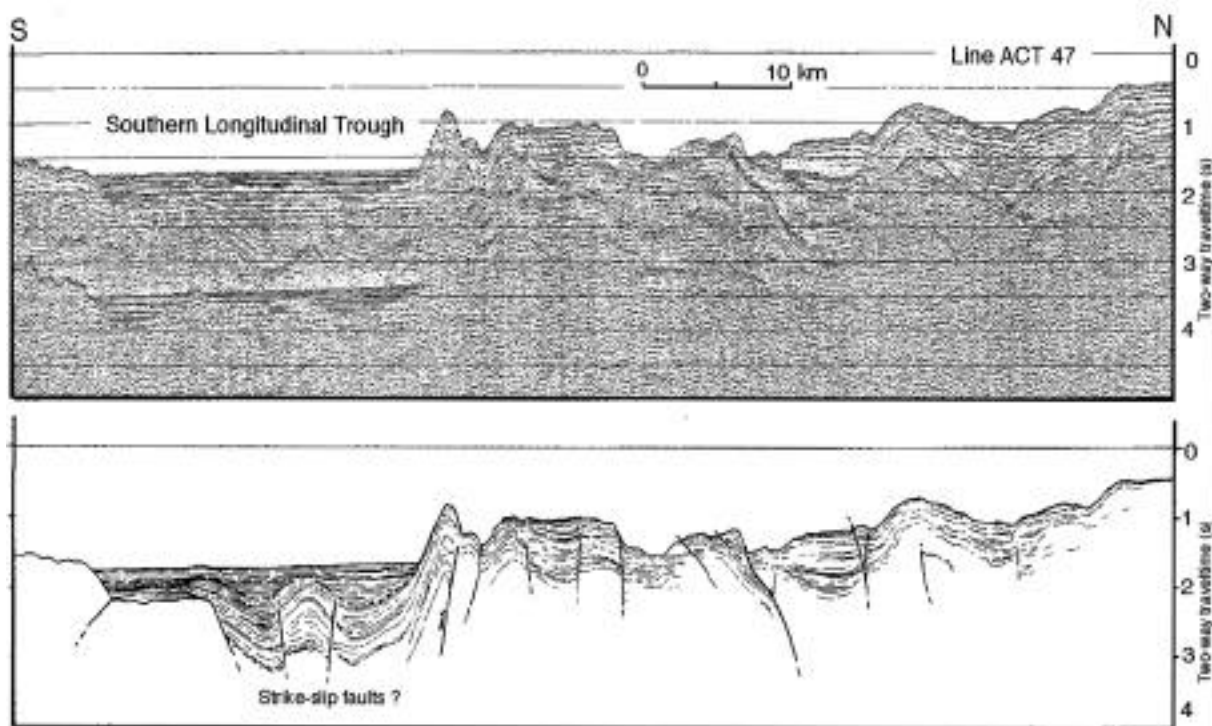


Figure 10. North-south seismic profile across the western part of the Southern Longitudinal Trough. (A) Migrated six-channel profile. (B) Line drawing showing the main geologic features.

series of imbricate scarps joins the southern tip of the Coastal Range to the main thrust, which marks the base of the eastern slope.

The north-south seismic profiles acquired during the ACT cruise show evidence of northwest-dipping thrusts in this area. For example, line ACT 36 (Fig. 15) shows a northwest-dipping thrust that offsets Holocene sediments of a small ponded basin lying on the back side of a submarine volcano, north of Lutao Island (Fig. 4). This zone of active faulting may be responsible for the drainage changes in the area east of Taitung. The seafloor in the upper part of a wide canyon, located near the base of the slope (Fig. 4) seems to have been offset by the fault scarp. Before thrusting and uplift in this area, this canyon may have been an active branch of the Taitung Canyon, allowing the sediments to be transported directly to the Huatung basin.

Clockwise rotation of the Coastal Range is documented by paleomagnetic studies (Lee et al., 1991a, 1991b). Rapid clockwise rotation of about 25–30° has occurred since the late Pliocene, with a propagation rate of the collision at about  $70 \pm 10$  km/m.y. from north to south. This result is in good agreement with the existence of a major transfer zone of deformation at the latitude of Taitung, which coincides with the 1000 m of difference in elevation between the Longitudi-

nal Valley and the Southern Longitudinal Trough, the clockwise rotation of the Coastal Range tectonic units, and the change in trend of the island arc (Fig. 4). Today, this transfer zone may account for the reversal of thrusting polarity, which occurs near Taitung, by allowing the simultaneous activity of both east-dipping thrust faults of the Coastal Range and west-dipping backthrust faults of the Huatung Ridge onto the arc. South of Taitung, the Lutao volcanic block is apparently rotated about 10° clockwise with respect to the Lanyu segment, assuming that this part of the arc was linear. GPS measurements on this island indicate a clockwise change in the azimuth of convergence direction of about 6° and a slight decrease in the convergence rate (about 3 mm/yr) from Lanyu to Lutao (Fig. 3). The 60-km-long segment of the volcanic edifice in this region is bounded to the west by the growing Huatung Ridge and is probably more intensively involved in the collision process in this area than to the south. The subsequent shortening and rotation would require thrusting along the northeastern flank of the arc segment, which is suggested by the break at the base of the slope and local mass wasting south-southeast of Lutao (Fig. 4). This hypothesis is not yet confirmed by seismic data, but we can consider that the Luzon volcanic arc undergoes collision-related deformation north of 22°25'N.

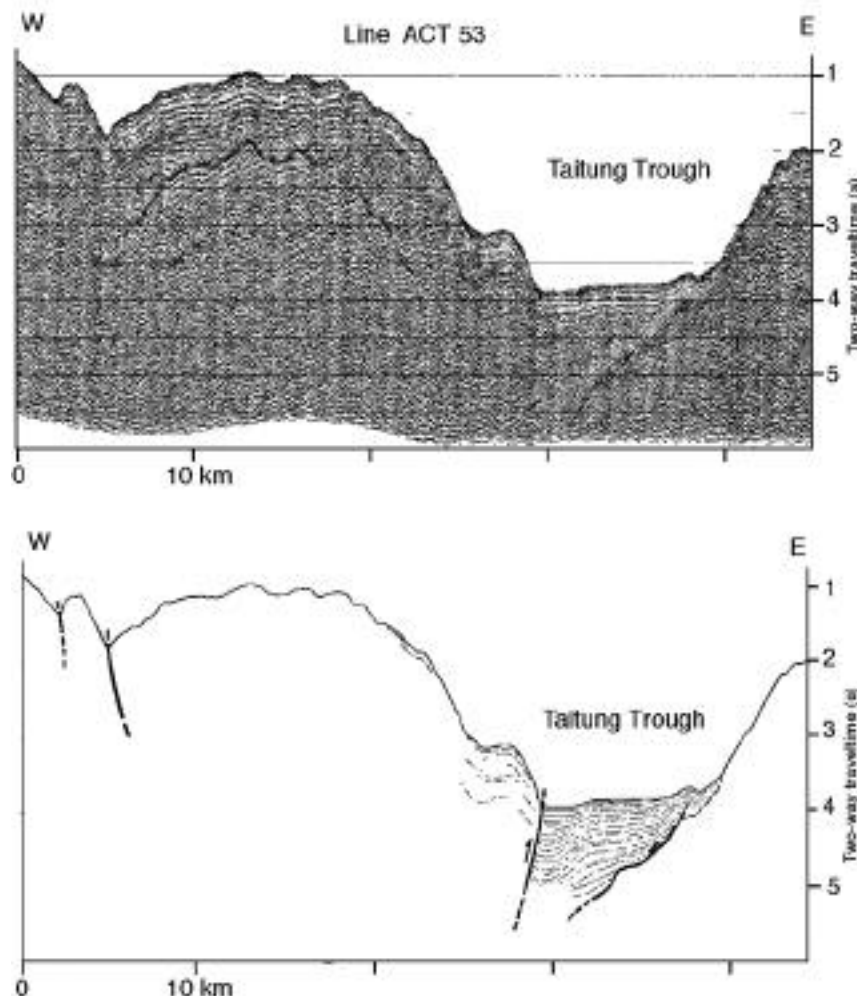


Figure 11. East-west seismic profile south of the study area. (A) Migrated six-channel profile. (B) Line drawing showing the main geologic features.

## DISCUSSION

Bathymetric and seismic data show that the forearc domain is very narrow along eastern Taiwan and that the arc is probably absent to the north of 24°N. Two hypotheses can account for this situation: (1) The volcanic arc was poorly developed or missing in this region of the Philippine Sea Plate, or (2) the frontal part of the arc was subducted during an earlier stage of the collision. Figure 16 presents two interpretive, lithospheric-scale cross sections in the collision zone that take into account our observations. The first (Fig. 16A) is located at the latitude of the Hengchun Peninsula; the second (Fig. 16B) is across the Central Range. The structural map of Figure 3 shows the two different tectonic domains involved in the collision process and their kinematics relative to Eurasia.

In the northern domain (north of 22°40'N), simple considerations based on geometry imply that the whole forearc area of the Luzon Arc has been underthrust beneath the Coastal Range between 22°50'N and 24°10'N (cross-section 4 of Fig. 5; also Fig. 16B). The detailed mechanism remains somewhat enigmatic, because a sliver of about  $90 \pm 20$  km width of forearc basement is suspected to have completely disappeared and there is no direct surface expression of such intra-arc subduction.

To arrive at the present situation in which the arc remnants of the Coastal Range tectonic unit (including dismembered parts of volcanic arc edifices, associated forearc, intra-arc and collisional basins) directly overthrust the already-exhumed metamorphic parts of the orogenic wedge, the forearc domain must be completely closed. The only way to do this is by underthrusting the basement lithosphere of the

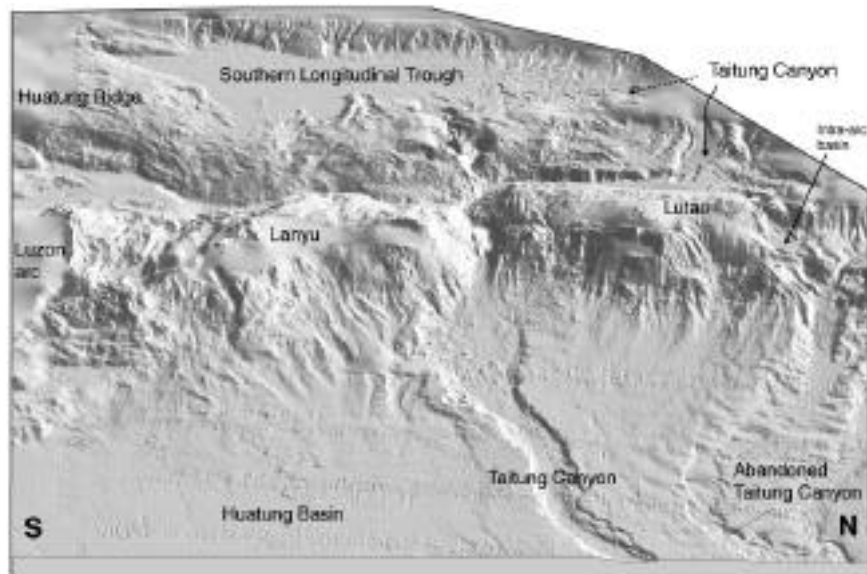


Figure 12. Shaded hill relief of the southern part of the study area (perspective view looking west).

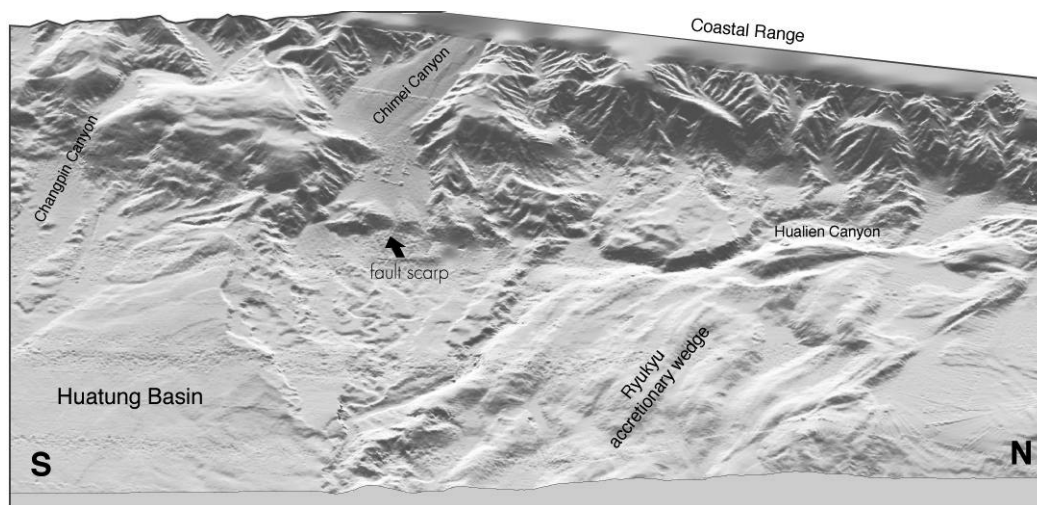


Figure 13. Shaded hill relief of the eastward-dipping slope offshore of the Coastal Range, (perspective view from the east). The relief map shows the prominent north-trending fault scarp cutting the base of the slope in the middle of the figure.

forearc beneath the arc. This process would allow enough time to exhumate the internal parts of the Taiwan thrust wedge, by processes involving: uplift of metamorphic rocks associated to major backthrusting against the rigid backstop formed by the basement of the Luzon forearc, tectonic underplating at depth beneath the Central Range, and erosion. The last (present) event is the westward thrusting of the Coastal Range on the Central Range.

In the southern domain (south of  $22^{\circ}40'N$ ), the collision process is less evolved, and the continental margin of China

is not yet subducting beneath the Philippine Sea Plate oceanic lithosphere, as suggested by the geometry of the intersection between the ocean-continent boundary with the Manila Trench. The major structural elements and morphology are different from those described to the north. The basement of the Hengchun Ridge and the Hengchun Peninsula could be either the Luzon Arc basement or the core of the former Manila oceanic accretionary wedge, as suggested by the absence of a magnetic signature (Liu et al., 1992). There are several ways to interpret the presence of this ridge: (1) it



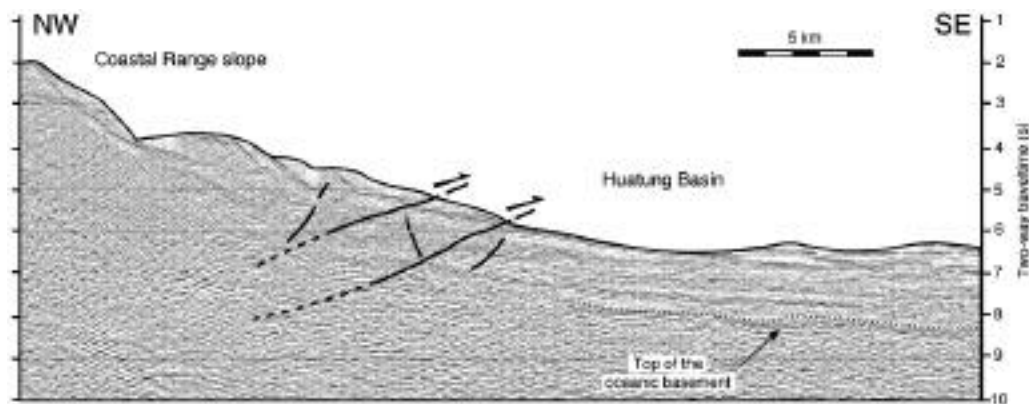


Figure 14. Northwest-Southeast seismic profile showing the west dipping thrust cutting the base of the slope. Ewing data, 160-channel profile.

could result from uplift above the subducting and underplating slope sediments beneath the older accretionary wedge (e.g., Reed et al., 1991); (2) it could result from duplexing of subducted crust below the ridge (Reed et al., 1992, 1997); (3) it could also correspond to the southernmost extension of the Central Range of Taiwan; or (4) it could be caused by the underthrusting of part of the forearc domain under the arc, inducing intense shortening and uplift in the back part of the accretionary wedge. The last interpretation is shown on the Figure 16A. This hypothesis is favored because south of  $22^{\circ}25'N$ , the Luzon arc is apparently slightly deformed by strike-slip faults (Lewis and Hayes, 1989), but the forearc domain is intensely shortened. Thus, the forearc basement (between the volcanic line and the accretionary wedge) should be subducting beneath the arc. The surface expression of forearc subduction is marked in the morphology and structures reflecting shortening in the orogenic wedge by (1) the major backthrusting of the Huatung Ridge and its piggy-back Southern Longitudinal Trough collisional basin and (2) out-of-sequence thrusting in the wedge that is induced by the eastward jump of the velocity break from the tip of the forearc basement (previous backstop of the wedge) to the front of the basement of the arc edifice (new backstop).

The Southern Longitudinal Trough could be the offshore equivalent today of the collisional basin in which the Lichi mélangé was deposited earlier, but further to the north. The Huatung Ridge has been shown to be made in part by folded and faulted sedimentary deposits of the basin. In such a case, they represent equivalents of the on-land Lichi mélangé, which is interpreted as the most recent suture zone between the Luzon arc and the Eurasian margin in Taiwan. This second "suture" would mark the recent jump of basement underthrusting to the east in the forearc. The age of the mélangé is disputed (e.g., Pelletier, 1985; Lu and Hsü, 1992; Huang et al., 1992). According to the observations made after the ACT survey, the age of the matrix must be younger to-

ward the south, because it consists of sediments that have been recently deposited in the Southern Longitudinal Trough, south of the Longitudinal Valley. The Longitudinal Valley, whose morphology is well expressed on land, has no similar expression offshore either to the north or to the south.

Because a 50-80-km-wide segment of the forearc basement (from magnetism) (Liu et al., 1992) has disappeared from section A to B (Fig. 16), we also suggest that the frontal part of the Luzon arc basement has been thrust down the Luzon subduction system along an east-dipping thrust fault. This segment of crust could be thus now located at depth beneath the Longitudinal Valley (see cross section B in Fig. 16). This interpretation, based on the geometry of the system, implies that the western side of a paleo-Longitudinal Valley fault (currently buried under the Coastal Range) had a top-to-the-east component of motion during convergence, allowing the uplift and exhumation of the Central Range together with the underthrusting of the Luzon forearc basement. Such forearc subduction with compressional failure and exhumation along the arc has been studied by physical and numerical modeling (Chemenda et al., 1997, 2001; Tang et al., this volume) and application of the models to Taiwan. Exhumation of the Central Range, associated with synorogenic surficial extension and apparent normal faulting along the eastern side of the range, has already been proposed by Crespi et al. (1996) on the basis of structural data collected across the Central Range.

Several observations based on ACT cruise data suggest that the collisional process is not continuous, but rather occurs in separate stages including reversal of thrust polarity, rotation, shortening and accretion. Indeed, it is very difficult to consider that the stage observed at  $23^{\circ}N$  results from the simple evolution of a stage at  $22^{\circ}N$ , which in turn results from the increasing compression of a stage at  $21^{\circ}N$ . Because of the obliquity of the plate convergence and the geometry of the ocean-continent transition in the Eurasian plate, the

Figure 15. North-south seismic profile showing the transfer zone of deformation that develops at the southeastern tip of the Coastal Range. (A) Migrated six-channel profile. (B) Line drawing showing the main geologic features.

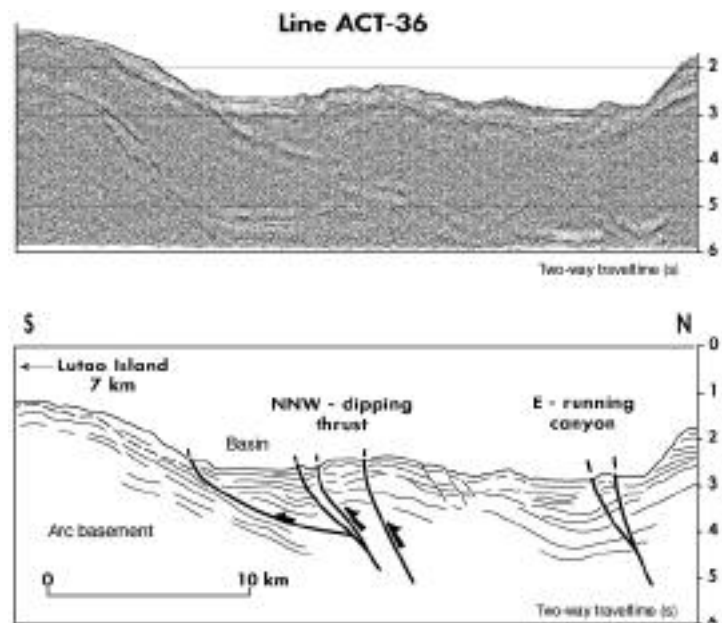
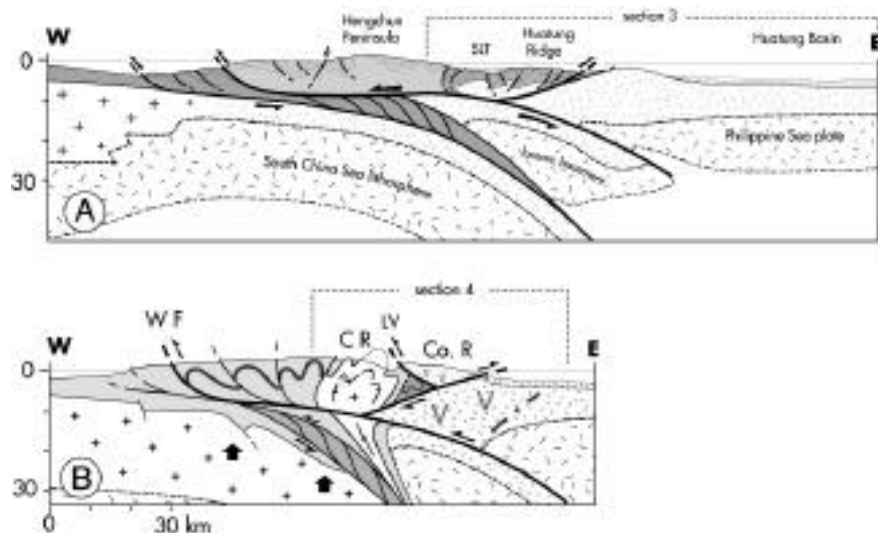


Figure 16. Interpretive geologic cross sections (A) south of the collision zone and (B) at the latitude of the Coastal Range. WF- Western Foothills, CR- Central Range, LV- Longitudinal Valley, Co.R- Coastal Range, SLT- Southern Longitudinal Trough. Locations of sections in Figure 1.



duration of the collisional stage increases toward the north (Suppe, 1981) and probably reaches a maximum at, and north of, 24°N where GPS stations show no significant northwestward motion of the Coastal Range relative to mainland China (Yu et al., 1997). North of 24°N, compressional stress is released offshore mainly along the Ryukyu Trench, but probably also in a more complex manner offshore Hualien (Lallemand et al., 1997b). The western termination of the Ryukyu accretionary wedge, and the complex area that marks the junction between the collision zone and

the Ryukyu Trench are exhaustively described in Lallemand et al. (1999), Font et al. (1999), and Dominguez et al. (1998).

#### ***Tectonic evolutionary model***

Figure 17 depicts a proposed model for the three-dimensional tectonic evolution of the Taiwan collision since 3 Ma. To allow a better understanding of collision mechanisms, this sketch shows only the limits of the different lithosphere units. Sediments of the accretionary wedges have

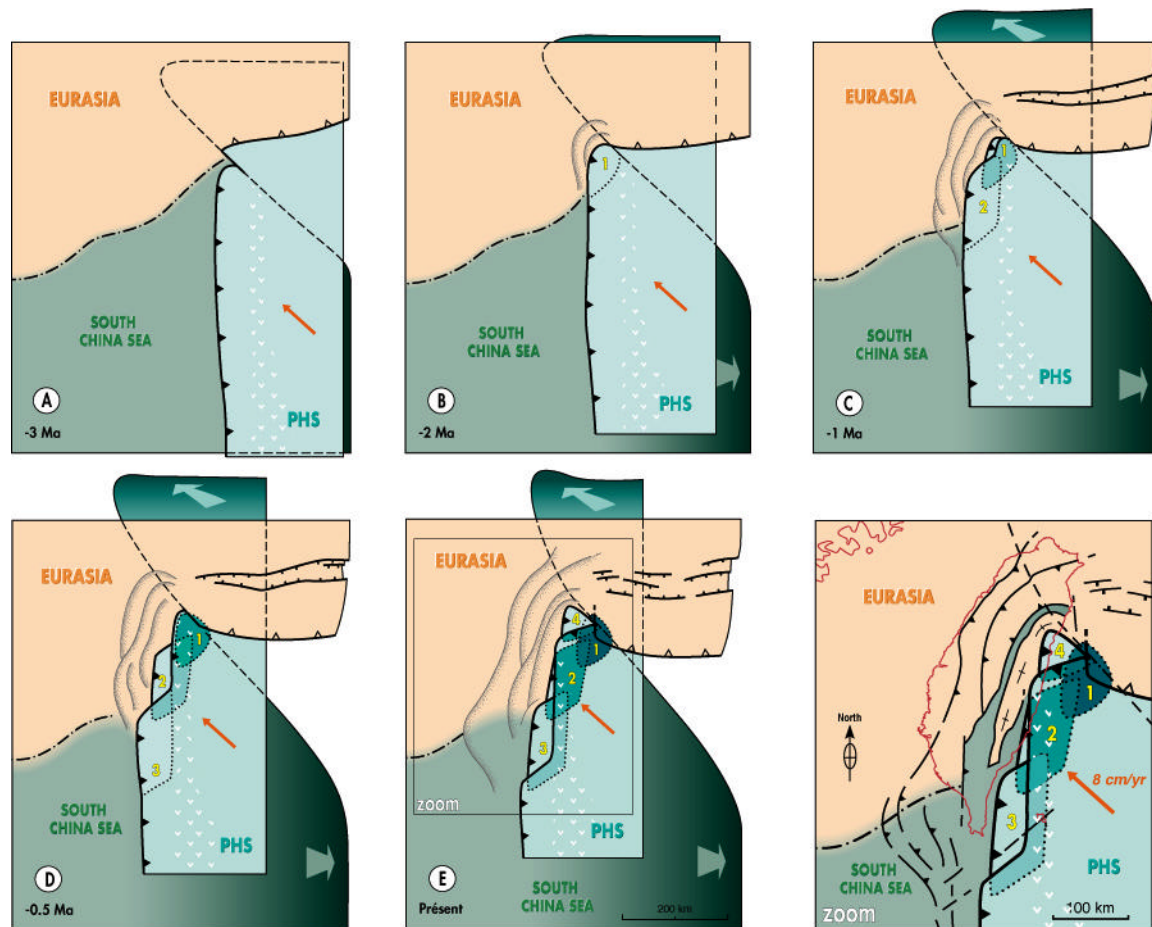


Figure 17. Three-dimensional geodynamic model of the Taiwan orogen. (A-E) The different stages since 3 Ma (see explanation in the text). Only the plate boundaries and the limits of the basement thrusts in the Philippine Sea Plate (PHS) are shown; thrust-wedge sediments have been omitted.

been omitted; thus, the growth of the collision thrust wedge is only suggested on the Eurasian plate. Figure 18 depicts the same stages of the tectonic evolution along a reference east-west cross section located at the same latitude as the present Central Range of Taiwan; the cross sections show the main tectonic units involved in the collision.

**First stage.** The Philippine Sea Plate was obliquely subducted beneath Eurasia to the north and the South China Sea oceanic lithosphere was subducted under the Luzon arc to the south (Fig. 17A). At that time (3 Ma), a major transform fault connected the two oppositely dipping subduction zones. The section of Figure 18A shows the beginning of continental-margin subduction beneath the Manila accretionary wedge.

**Second stage.** The northwestern corner of the Philippine Sea Plate deformed the continental margin of China at

1.5 Ma (Fig. 17B), which began to subduct, inducing a stress increase in the forearc lithosphere of the Philippine Sea Plate. Figure 18B shows the deformation of the margin and the early stages of development of the Central Range. This tectonic unit corresponds to an offscraped slice of the upper crust in the basement of the continental margin, strongly deformed and metamorphosed during burial under the Philippine Sea Plate. Increasing stress in the Philippine Sea Plate induces failure of the forearc lithosphere in the weak domain of the volcanic arc (and arc subsidence). A set of conjugate thrusts develops within the arc lithosphere.

**Third stage.** At 1 Ma, a slice of the forearc lithosphere (unit 1 in Fig. 17C) was thrust beneath the arc. Collision-related deformation migrated to the south, involving stress increase in a new domain of the Philippine Sea Plate. Figure 18C shows the different processes that occurred during this

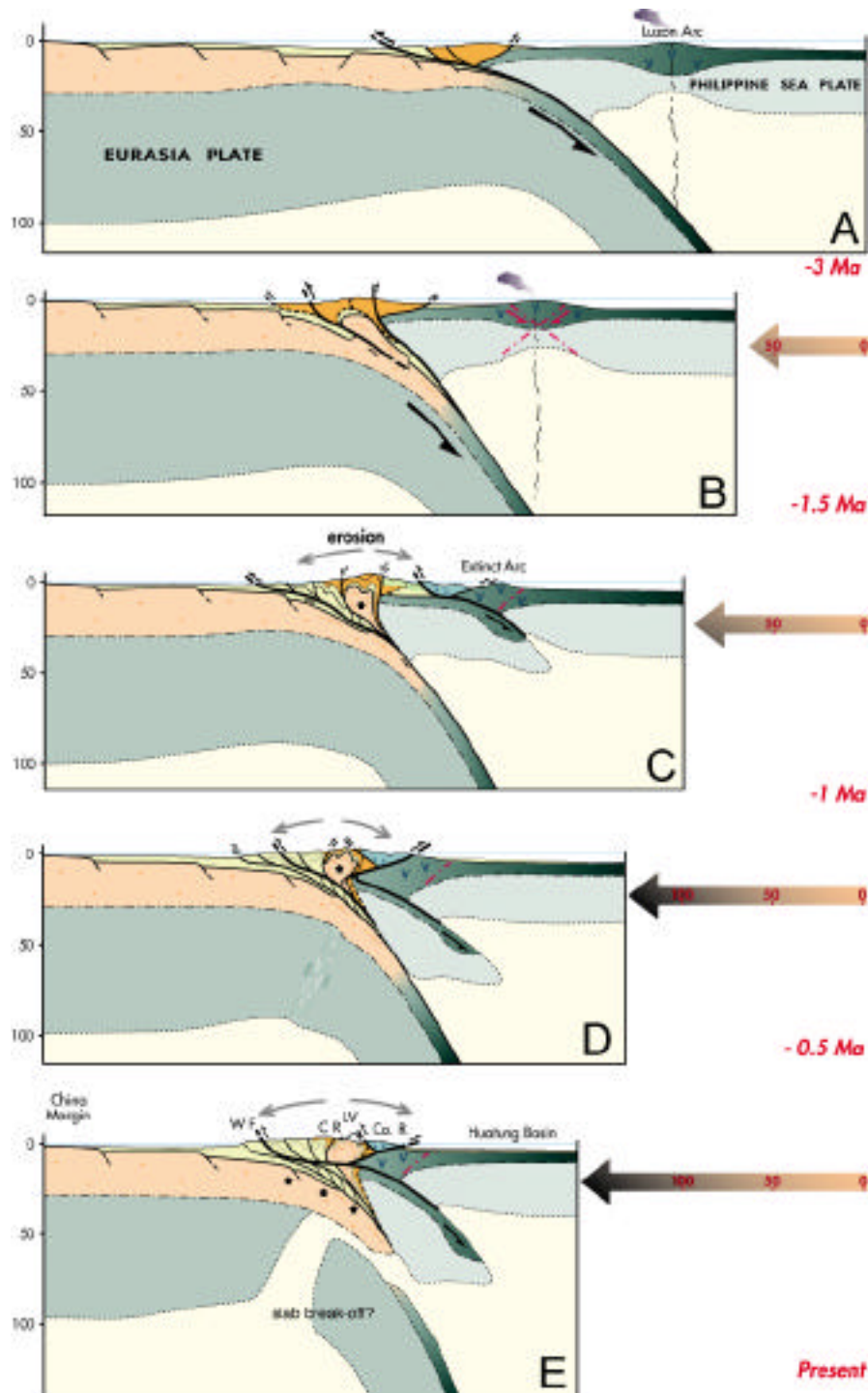


Figure 18. Tectonic evolutionary model of the Taiwan orogen since the beginning of the collision (see explanation in the text). The sections are correctly balanced. WF- Western Foothills, CR- Central Range, LV- Longitudinal Valley, Co.R- Coastal Range. A slab break-off is suggested in the present stage (E) as proposed in Lallemand et al., 2001



complex evolutionary stage. To the east, the volcanic activity of the arc stopped because of the subduction of the forearc sliver, which cut the magma source. West of the extinct arc, a complex collisional basin developed, mainly filled by sediments eroded from the Taiwan mountain belt. A new thrust wedge developed against the arc edifice, composed of volcanoclastic sediments of the early forearc basin, detrital sediments of the collisional basin, and offscraped volcanic rocks from the forearc basement. This feature is the northern early equivalent of the present-day Huatung Ridge. To the west, continuing subduction of the continental margin involved the growth of a large sedimentary wedge by stacking of thick sedimentary sequences of the passive margin. In the core of the growing wedge, metamorphic rocks of the Central Range were progressively exhumed and rose through the overlying rocks of the old oceanic wedge owing to the combined effects of erosion of the internal domain of the wedge and probable underplating at depth favoring uplift. The metamorphic rocks rose along the subvertical surface marking the western extent of the backstop formed by the forearc lithosphere. The present-day western boundary of the Central Range is characterized by subvertical faults with apparent normal offsets. Depending on their dip during the uplift, they could be normal faults (eastward dip) developed in a convergent setting, or steep backthrusts (westward dip). As in classical accretionary wedges, the dip of such faults would be controlled by the shape and dip angle of the backstop (Malavieille et al., 1991) (in our case, the shape of the forearc lithosphere, which is poorly known). During uplift of the internal parts of the mountain belt, the rocks of the early oceanic accretionary wedge (including ophiolite blocks of former mélanges) resting on top of it, were deeply eroded and became the source for the olistostromal blocks currently included in the Lichi mélange. Most of these sediments were deposited in collisional basins during shortening of the forearc domain and were later involved in thrusting.

**Fourth stage.** The southward migration of deformation and the subduction of a second slice of the forearc lithosphere (unit 2 of Fig. 17D) occurred at 0.5 Ma, whereas farther south, another domain (unit 3 of Fig. 17D) of forearc lithosphere was subjected to a stress increase. Foreland deformation developed to the west in the Taiwan Strait. Offscraped remnants of the forearc domain including forearc- and intra-arc sediments were tectonically mixed with sediments of former collisional basins. A new mechanism allowed exhumation to continue. The asymmetrical mechanism of wedge growth by forward thrusting (e.g., Malavieille, 1984) that had been operating in the Taiwan region up to this time was replaced by a more symmetrical evolution with significant backthrusting (Fig. 18D). Uplift therefore occurred because of the conjugate effects of east-dipping, forward out-of-sequence thrusting, and west-dipping backthrusting. The forearc domain was shortened significantly at this stage.

**Present situation.** Figure 17E shows a third unit of forearc lithosphere to the south that has begun subducting, whereas lithosphere of unit 2 is completely subducted. The

tip of the arc basement now enters in the collision process, indenting the Central Range, which is now cut by a east-dipping, out-of-sequence thrust (Fig. 18E). The main tectonic features of present-day Taiwan are presented in the Figure 17F.

Two main hypothesis may account for the present evolution of the collisional process in this domain.

1. Increasing stress in the northernmost domain of collision has induced the propagation of a northwest-trending transform-tear fault that bounds the Ryukyu slab to the southwest. Failure in the oceanic lithosphere has resulted in the detachment of a fourth tectonic unit to the north (unit 4 of Fig. 17E). In this domain, most of the convergence occurs southeast of this unit probably on east-dipping blind thrusts merging below the easternmost part of the Ryukyu accretionary wedge and joining the basal décollement in the Ryukyu Trench system. This hypothesis is depicted in Figure 17E.

2. As proposed by Chemenda et al., (1997), after removal of the forearc crust, a major west-dipping thrust developed in response to indentation by the arc lithosphere and cut through the continental lithosphere of the China margin (see Fig. 12D, p. 267, and Fig. 13, p. 268, in Chemenda et al. [1997]). This process results in the development of a new subduction zone that propagates southward.

Both of these mechanisms could explain the lack of displacement shown today by GPS measurements in northern Taiwan.

**Geophysical constraints.** Numerous geophysical studies help to define the general structure of the Taiwan collisional area. Among them, several recent seismological observations may be consistent with the underthrusting of part of the forearc crust under the arc (Rau and Wu, 1995, 1998; Wu et al., 1997; Kao et al., 1998; Cheng et al., 1998, and this volume; Lallemand et al., 2001). Figure 19 shows three interpretive sections (locations in Fig. 1) of the present stage of the collision process and its evolution in space from north to south of the orogen. Seismicity data from global (Engdahl et al., 1998) and regional networks (Wu et al., 1997; Cheng et al., 1998) have been projected onto the three sections arranged from north to south.

In particular in the section that crosses southern Taiwan (Fig. 19B), two east-dipping bands of seismicity can be distinguished: a broad, steeply dipping ( $50^{\circ}$ - $60^{\circ}$ ) band (on the left), which represents the plate boundary and the subducting lithosphere of the Chinese margin, and a narrower, more shallowly dipping band beneath the arc at 20-40 km depth (on the right in Fig. 19B). The latter corresponds well to the  $20^{\circ}$ E-dipping underthrusting focal plane shown in recently published fault-plane solutions (Kao et al., 1998) and supports eastward-directed underthrusting of the forearc beneath the Luzon arc south of Lanyu. A high-velocity zone, at a depth range of 15-50 km, has been imaged by Rau and Wu (1995) under the Coastal Range and the Philippine Sea. Detailed seismic tomography studies by Cheng et al. (1998 and this volume) also show two zones of high seismicity and a prominent high-velocity anomaly in the middle to lower crust, which could correspond to the underthrusting of

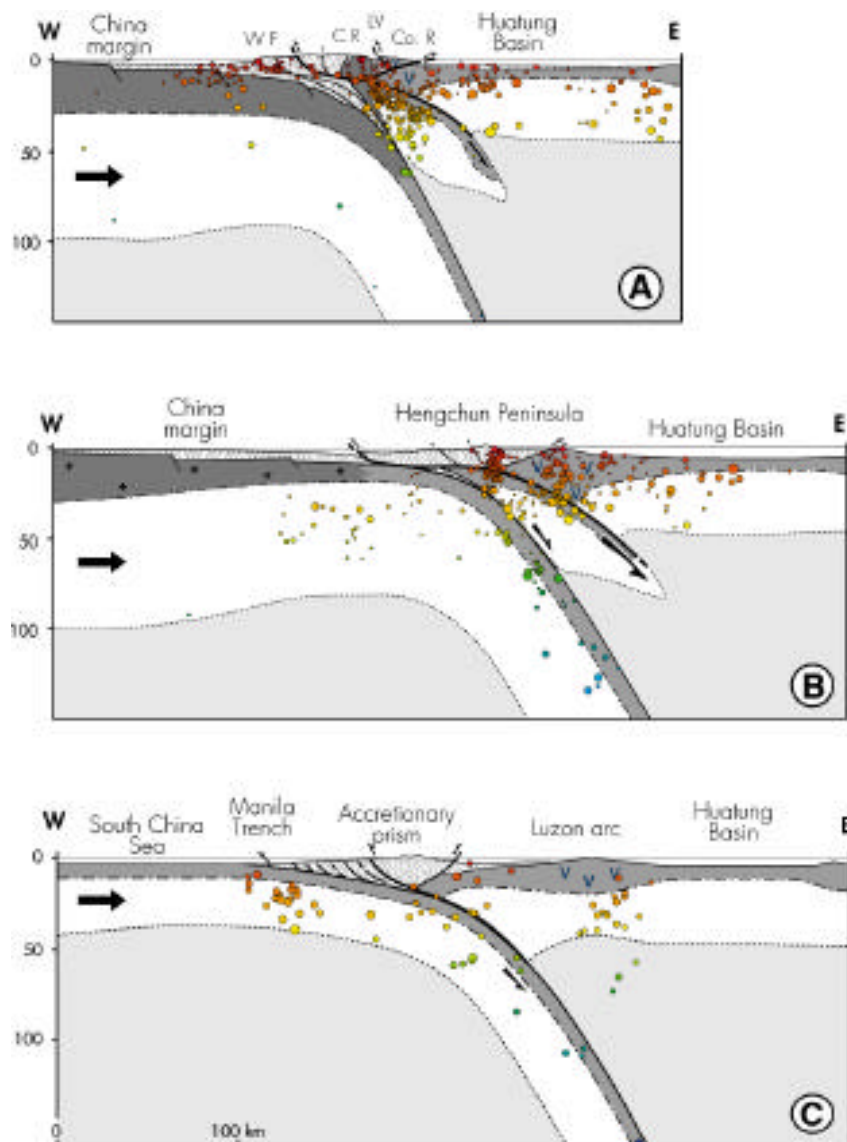


Figure 19. East-west sections of the present stage of collision showing its evolution in space from the south to the north of the orogen (for location, see Fig. 1). Seismicity data from global (Engdahl et al., 1998) and regional networks (Wu et al., 1997; Cheng et al., 1998) have been projected onto the three sections. (A) section at 23°N, across the Taiwan mountains. (B) Section at 22°20'N, across the Hengchun Peninsula. (C) Section at 21°N. WF- Western Foothills, CR- Central Range, LV- Longitudinal Valley, Co.R- Coastal Range

forearc crust.

## SUMMARY AND CONCLUSIONS

The progressive subduction of the continental margin of China induces (1) to the south, major eastward back-thrusting and shortening of the forearc domain between the former oceanic accretionary wedge and the Luzon arc volcanic edifice and (2) to the north, accretion of parts of the arc domain to the collisional belt associated with westward thrusting and block rotation.

Our marine observations show the complex interactions of tectonic deformation, sediment dispersal, and basin development along eastern Taiwan.

In the southern domain, the Longitudinal Valley disappears offshore to the south below the Southern Longitudinal Trough, which is a collisional basin filled with Holocene orogenic sediments lying unconformably on deformed and folded strata of the former forearc domain. Transpressive deformation has played an important role during the development of the Southern Longitudinal Trough. Present deformation has jumped to the east, and it is characterized by the growth of a sedimentary ridge (the Huatung ridge, the rear part of the former Manila oceanic accretionary wedge including forearc and intra-arc sequences), which overthrusts the basement of the island arc. Part of the island arc (Lutao area) is affected by subsequent shortening.

In the northern domain, at the base of the eastern slope of the Coastal Range, prominent fault scarps suggest active eastward thrusting of parts of the arc (volcanic edifices and intra-arc or forearc sedimentary deposits) onto the oceanic crust of the Philippine Sea plate. The northernmost part of the Coastal Range, is presumably being accreted to the rest of Taiwan.

A N50°E-trending transfer zone of deformation accommodates the differential motion and rotation of the northern and southern tectonic units.

The relationship of the Coastal Range and the offshore structures along eastern Taiwan to the distribution of canyons and deformation offshore Hualien and Ryukyu Trench fits the evolution described for the region.

Structural observations show that the forearc basement of the Luzon arc no longer exists north of the latitude of Taitung. A model is proposed for the "missing" part of forearc crust in the region of collision and the tectonic evolution of the Taiwan orogen.

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