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Arc-Continent Collision in Taiwan: New Marine Observations and Tectonic Evolution

Jacques Malavieille, Serge E. Lallemand, Stephane Dominguez, Anne Deschamps

Laboratoire de Géophysique, Tectonique et Sédimentologie UMR 5573, UM2-CNRS, CC. 60, 34095 Montpellier, France, 33-467-14-36-58; email: malavie@dstu.univ-montp2.fr

Chia-Yu Lu

Department of Geology, National Taiwan University, 245 Chou-Shan Rd., Taipei, Taiwan, e-mail: lu@sun03.gl.ntu.edu.tw

Char-Shine Liu, Philippe Schnürle

Institute of Oceanography, National Taiwan University, P.O. Box 23-13, Taipei, Taiwan.

and the ACT Scientific Crew

J. Angelier, J.-Y. Collot, B. Deffontaines, M. Fournier, S.-K. Hsu, J.-P. Le Formal, S.-Y. Liu, J.-C. Sibuet, N. Thareau and F. Wang

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. The Philippine Sea Plate (PHS) began colliding with the Eurasian continental margin in Pliocene time. Because of the obliquity of plate convergence, the collision has propagated through time from north of Taiwan to the south with the more advanced stages being presently observed to the north, whereas the subduction of the oceanic lithosphere of the South China Sea beneath the PHS occurs to the south. Offshore, the collision zone is characterized by deformation of the arc including the forearc region to the south. This active tectonic domain absorbs a significant amount of shortening between the Eurasia margin and the PHS, which is moving towards N 310° E at about 8 cm/yr relative to Eurasia. Swath bathymetry and backscattering data, together with seismic reflection and geopotential data obtained during the ACT 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.

In the southern domain, left-lateral transpression is recorded by deformed and folded series of the forearc domain that are unconformably overlain by collision-derived sediments of the Southern Longitudinal Trough (SLT). Today, the loci of deformation has jumped to the east and it is characterized by the growth of a sedimentary ridge (the Huatung ridge, rear portion of the former Manila oceanic accretionary wedge including forearc and intra-arc sequences), which overthrusts the basement of the island arc.

In the northern domain, north of 22°30'N, active westward thrusting of the Coastal Range (remnants of the island arc and forearc basins) over the Lichi mélange develops onland along the Longitudinal Valley. Offshore, at the base of the eastern slope, prominent fault scarps suggest an active eastward thrusting of parts of the arc (volcanic edifices and intra-arc or forearc sediments) onto the oceanic crust of the Philippine Sea Plate. It accounts today for part of the convergence. The

northernmost domain of the Coastal Range, is presumably being accreted to the rest of Taiwan. A N50°E trending transfer zone of deformation accomodates the differential motion and rotation of the northern and southern tectonic domains.

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 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 of 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.

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 presently in growing orogens.

The young Taiwan orogen has been the subject of study for many years, mainly onland [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 constrained. 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 (Figure 1). This paper focusses on the active deformation occurring south and along the Coastal Range of Taiwan and its connection with the southern Ryukyu subduction zone (published in [Lallemand et al., 1999]).

Several geophysical cruises have been conducted in the offshore area of Taiwan since the early 90's, providing multichannel and OBS refraction seismics [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], gravity and magnetic data [e.g., Hsu et al., 1998]. In 1996, EM12 Dual multibeam bathymetry, side-scan sonar imagery, 6 channel seismic reflection 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., 1997]. 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 which was, and is currently, deforming due to the subduction of the Chinese continental margin beneath the Luzon arc. These newly acquired data greatly contribute to constrain 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 (PHS) 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 PHS)? Does the Central Range belong to the Chinese continental margin or to the PHS forearc domain (representing former parts of 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 stage? Other questions directly resulting from the previous ones will also be discussed, for example: Does the Longitudinal Valley, which was often considered as the onland 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 the last 4 Ma.

GENERAL SETTING

Two plates are involved in the complex tectonic setting that surrounds the Taiwan orogen, the Philippine Sea plate (PHS) and the Eurasian Plate (EUR) (Figure 1).

Northeast of the Taiwan area, the PHS is being subducted beneath the Ryukyu Arc, which belongs to the Chinese continental margin. The Okinawa backarc basin has 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 Island, the oceanic lithosphere beneath the South China Sea (SCS) subducts beneath the PHS, inducing the volcanism of the Luzon arc. The relative motion between the PHS and EUR results 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 PHS is presently moving northwestward, with respect to the EUR [Seno, 1977; Seno et al., 1993]. Recent GPS measurements on Lanyu Island over the 1990-1995 period provide a precise N 306° ± 1° azimuth for the convergence at a rate of 80-to-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 PHS 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 associated Manila Trench, is probably Early Miocene in age, according to the oldest volcanic rocks (andesites) sampled in the Coastal Range of Taiwan by Juang and Bellon [1984]. The northernmost present activity of the arc is observed at the latitudes of the Batan Islands. Younger ages, as recent as 30 kyr, were also found using K-Ar datings on Lutao and Hsiaolanyu (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 Lutao and Lanyu islands [Yang et al., 1996], or even further north if younger volcanic rocks have been eroded from the uplifted Coastal Range [Richard et al., 1986].

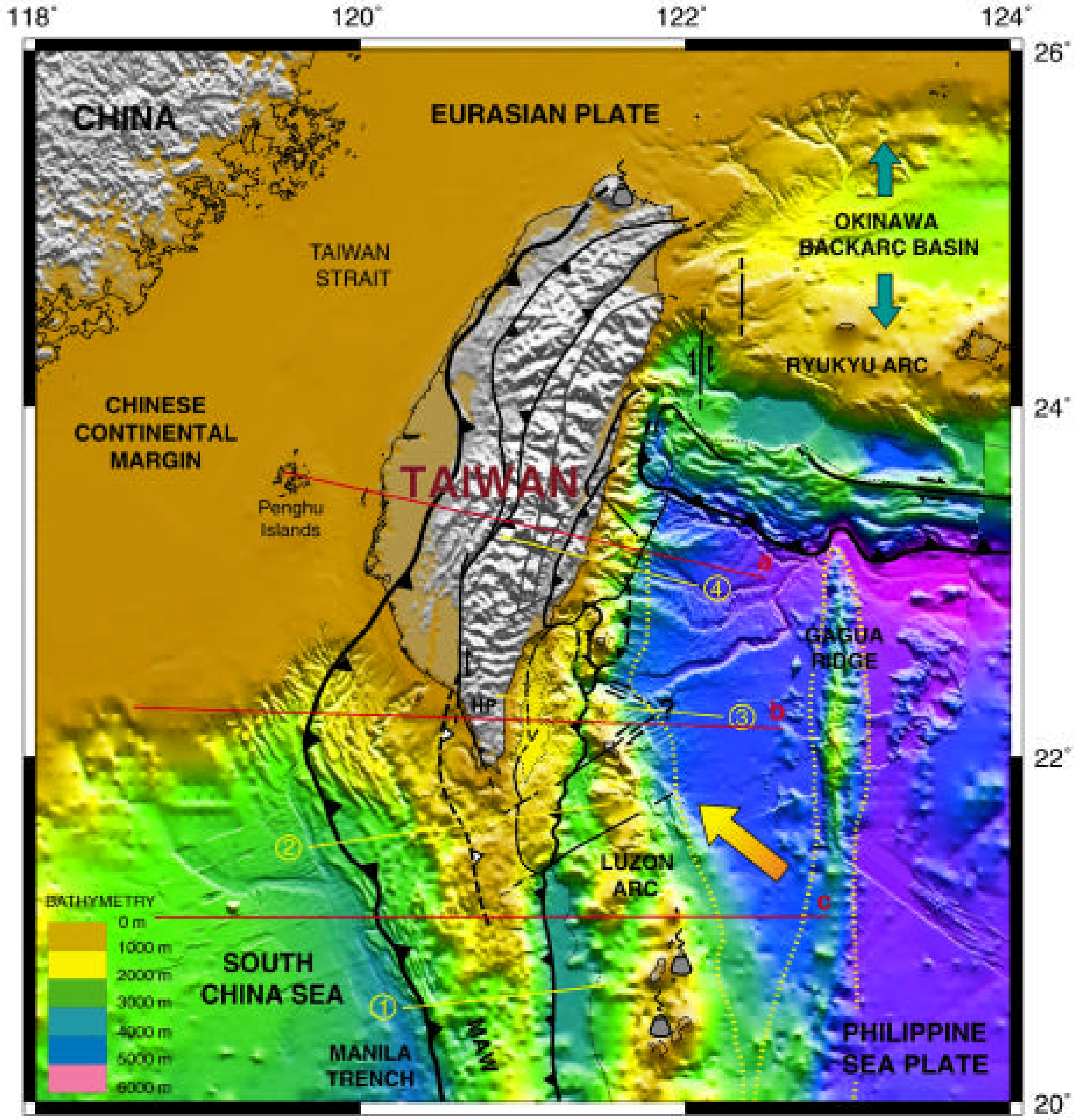


Figure 1: Geodynamic setting of the Taiwan orogen and location of the sections. The main tectonic units are shown on the shaded topographic view. MAW, Manila Accretionary Wedge ; HP, Hengchun Peninsula.

A progressive increase in continental contamination of andesitic magmas correlates with progressively younger ages in Coastal Range volcanic rocks. This 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 NNW-SSE spreading migrated southwestward [Briais and Pautot, 1992]. The fossil spreading ridge is presently 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 (Figure 1) and is still growing today south of 21°20' N [Hayes and Lewis, 1984 ; Lewis and Hayes, 1984 ; 1989]. North of 21°20' N, the wedge becomes incorporated in the arc-continent collision domain, involving progressively Early-Middle Miocene slope and trench sediments [Reed et al., 1992]. The southern tip of Taiwan Island, called the Hengchun Peninsula, extends offshore southward as far as 20°30'N in latitude, as the Hengchun Ridge (Figure 1). This ridge is generally considered as the uplifted internal domain of the oceanic accretionary wedge presently suffering the effects of the collision [Lundberg et al., 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 portion 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, with up to 5 km of recent orogenic sediments deposited on 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 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 presently exposed in the Western Foothills of Taiwan [Suppe, 1980; Davis et al. 1983] with part of the history and tectonic events of the arc-continent collision registered in the young and non-metamorphosed 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° 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 following. The sedimentary cover of the Chinese continental margin (see Taiwan Strait in Figure 1) was accreted in the northwest part of the island, and it is still accreting in the southwest, 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 Hsüeshan Range [Ho, 1982; 1988]. During convergence, they were progressively accreted to the collision prism along a series of west vergent thrusts.

The Central Range includes the Eocene and Miocene (lack of 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 and sandstone 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 Plio-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 PHS 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 PHS, as attested by the GPS velocities of 63 ± 9 mm/yr in the direction of N314° ± 8°, except north of 23°40'N where rates dramatically drop to 8-43 mm/yr in the azimuths N292° to 352° [Yu et al., 1997]. About 8 cm/yr of plate convergence is taken up in the offshore area north of 24°N, while south of 24°N, the convergence is almost entirely distributed across the island, with 3 cm/yr accomodated in the Longitudinal Valley area [Angelier et al., 1997], and across the other thrusts of the Coastal Range shown on Figure 1 [Yu et al., 1997]. Lundberg and Dorsey [1990] estimated the uplift rate of Quaternary marine terraces along the Coastal Range in excess of 6 mm/yr.

MARINE OBSERVATIONS AND DATA ACQUISITION

The ACT cruise and KAONOUM transit aboard the R/V L'Atalante mapped an area of about 67,500 km^2 at 10 knots during 15 days with 100% bathymetric and backscattering coverage (Figure 2a). Tracks were generally oriented parallel to the structures (Figure 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 small-scale bathymetric features and to variations in the nature of the seafloor. Subbottom (3.5 kHz) and reflection seismic profiling, 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. 6-channel streamer was deployed with two 75 inch^3 GI guns at a pressure of 160 bars. The guns were fired in an harmonic mode to generate a source signature centered on 20 Hz to enhance subbottom penetration of energy. Shot intervals were approximately 50 m. Seismic data were processed using ProMAX software to obtain post-stack time migrated profiles.

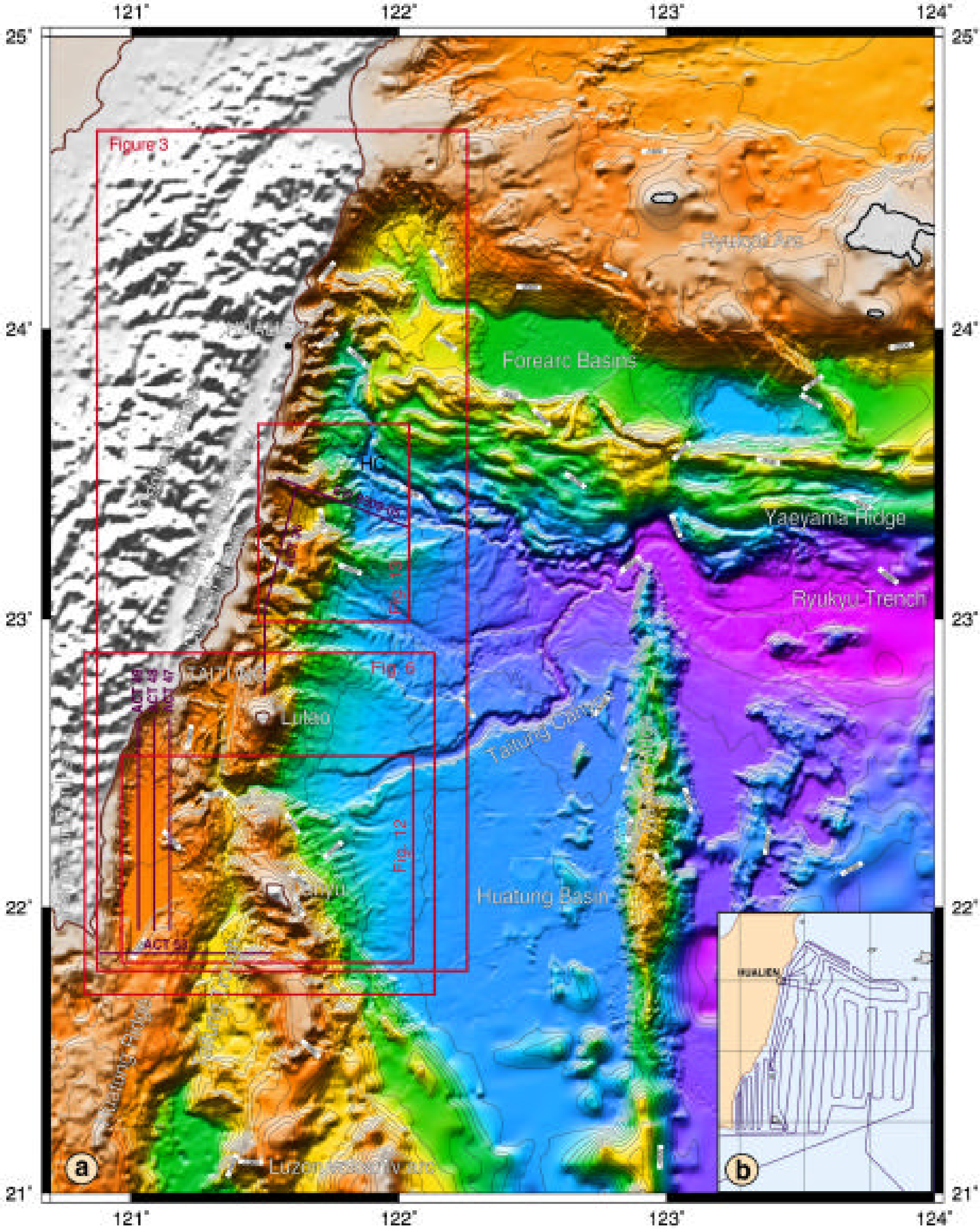


Figure 2: a) Bathymetry of the collision zone offshore east of Taiwan. Location of the main morphotectonic units and the seismic lines described in the paper are shown. HC, Hualien Canyon. b) Ship tracks.

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

Arc-Continent collision is classically considered to be the result of subduction of the continental margin of China under the Luzon island arc (Figure 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 down to 21°N.

Main structural elements

The main tectonic features are defined on the structural map in Figure 1, Figure 3 and detailed bathymetric map in Figure 4.

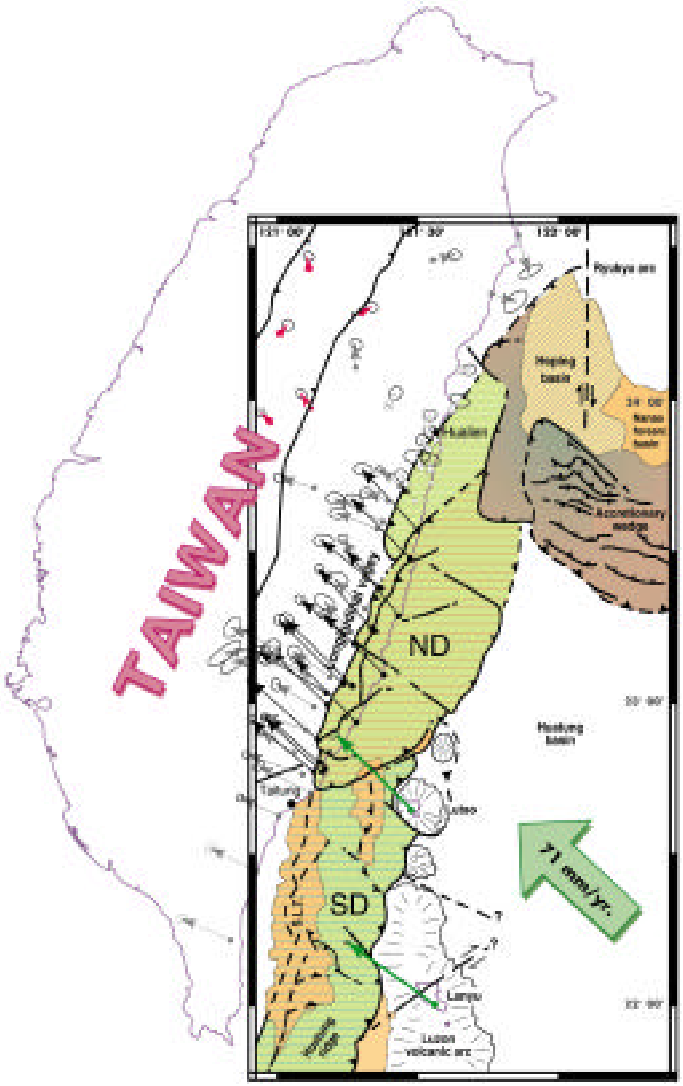


Figure 3: Schematic tectonic map of the study area showing the kinematics of the main tectonic units (GPS data after Yu et al., [1997]. The 95% confidence ellipse is shown at the tip of each velocity vector). ND, Northern tectonic Domain ; SD, Southern tectonic Domain.

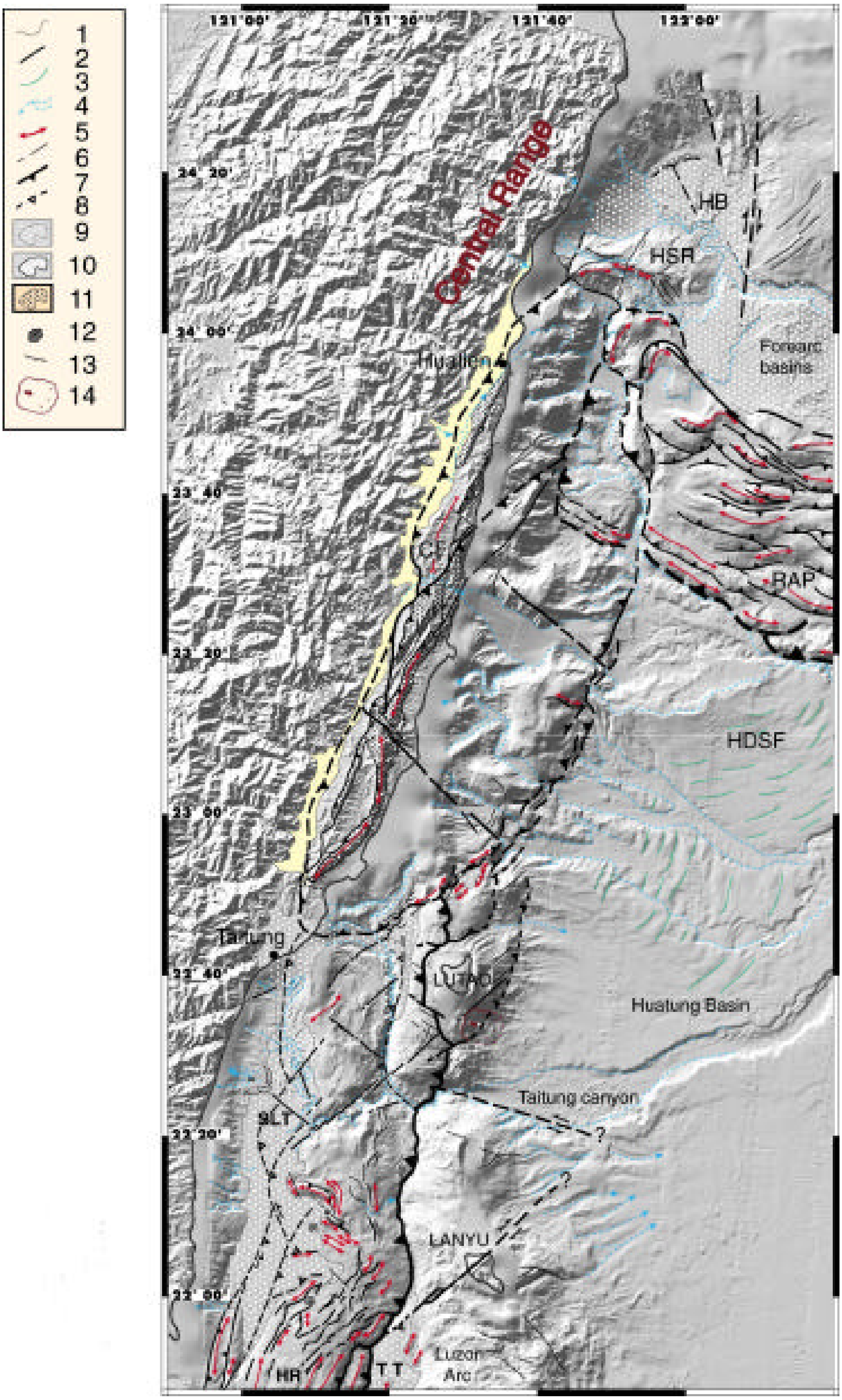


Figure 4: Structural map of the study area offshore Taiwan. Geological features are drawn on the bathymetry (shaded view, lightening N 310°E). 1 - geologic boundary, 2 - fault, 3 - large scale mud waves, 4 - drainage, 5 - fold axis, 6 - minor fault, 7 - thrust, 8 - inactive thrust, 9 - recent collisional 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 ; TB, Taitung Basin ; CF, Chimei Fault ; HSR, Hsingsen Ridge ; HB, Hoping Basin ; HDSF, Hualien Deep Sea Fan ; RAP, Ryukyu Accretionary Prism.

Two structural domains constitutes the collisional area :

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

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 Hoping basin has developed.

The boundary between the two structural domains is characterized by a transfer zone of deformation which accomodates their different mechanical evolution. The map of 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 E-W geological cross sections (drawn with no vertical exaggeration) are presented, based on the analysis of data from the ACT cruise. These sections illustrate the major structural changes occurring from the south to the north, due to the increasing involvement of the Chinese continental margin in the subduction and collision. The interpretation proposed at depth for the four sections and the deformation mechanisms involved will be explained and discussed below.

Section 1 (Figure 5), 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 which 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 due 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 (Figure 5), 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 taper, 2) an uplifted domain of the wedge (the Hengchun ridge) bounded by a slope break and characterized by a high taper upper-slope, 3) a smaller ridge, composed by deformed strata of part of the former wedge and forearc sediments, separated from the rear of the wedge by a narrow N-S valley (see also on Figure 1 map). Reed and others [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 (Figure 5) shows the development of a recent collisional basin (the Southern Longitudinal Trough) between the eastern flank of the Hengchun Peninsula and the Huatung Ridge overthrusting onto the Luzon arc [Lundberg, 1988] (Figure 1). Along this section again, major shortening occurs today in the forearc domain [Lundberg et al., 1997]. The Southern Longitudinal Trough (SLT) is filled in part 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 volcaniclastic sediments and which ended south of the Huatung Ridge, at about 21°N20'. From 22°40'N to about 24°N, the collision is completed and the forearc domain is drastically reduced.

Section 4 (Figure 5) shows the active westward thrusting of the Coastal Range on the formerly exhumed metamorphic rocks of the Central Range. The onland Coastal Range and its offshore slope continuation is composed by offscraped parts of the former volcanic arc edifice, intra-arc basins and strongly deformed forearc strata. This tectonic unit may be decoupled from the PHS oceanic basement by an east vergent thrust located close to the base of the slope (Figure 1).

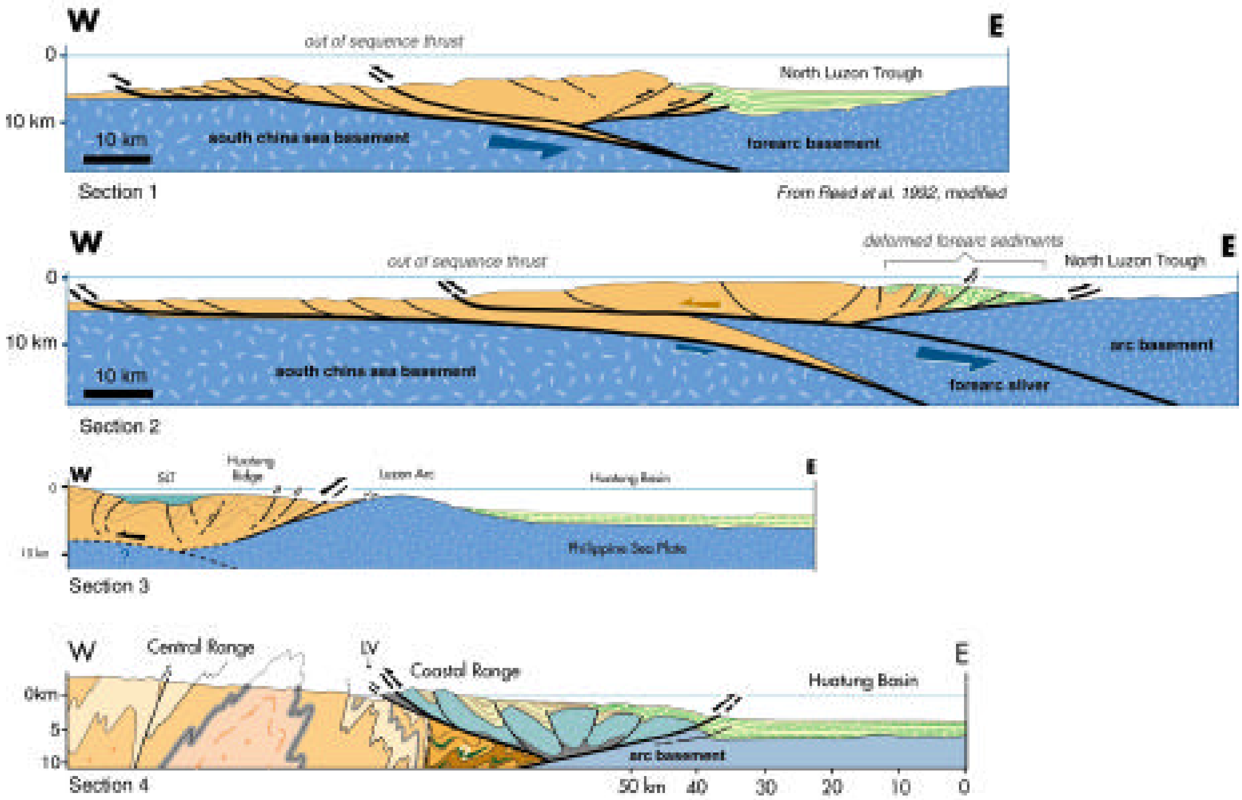


Figure 5: Geologic cross sections (same scale, no vertical exageration). Section 1 and 2 are based on Reed et al., [1992]. See location of sections on Figure 1.

Deformation in the southern structural domain.

The Southern Longitudinal Trough and surroundings. The SLT (Figure 4) is a proximal orogenic basin developed in a forearc position [e.g., Lundberg, 1988; Lundberg, 1997; Fuh et al., 1997]. It is elongated in a N-S direction 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. To the west, it is bounded 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 SLT.

Today, sediments are mainly supplied from the onland peninsula through numerous E-W trending gullies. Most of the sediments coming from the Central Range through the Longitudinal Valley are dumped into the Taitung Canyon (see north of perspective view in Figure 6), but some of them are collected by the tributaries of a canyon, which begins in the northern part of the SLT, turns sharply east, meanders across the Huatung Ridge near latitude 22°20'N and finally flows into the Taitung Canyon position [Lundberg, 1988; Lundberg et al., 1997] (Figure 4). The Central Range source for recent orogenic sediments is 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 SLT 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 backscatter images suggesting the presence of coarse sediments or gravels (Figure 7). The E-W trending gullies on the western border of the SLT are also reflective, while the braided channels on the floor of the SLT are much less reflective. This 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.

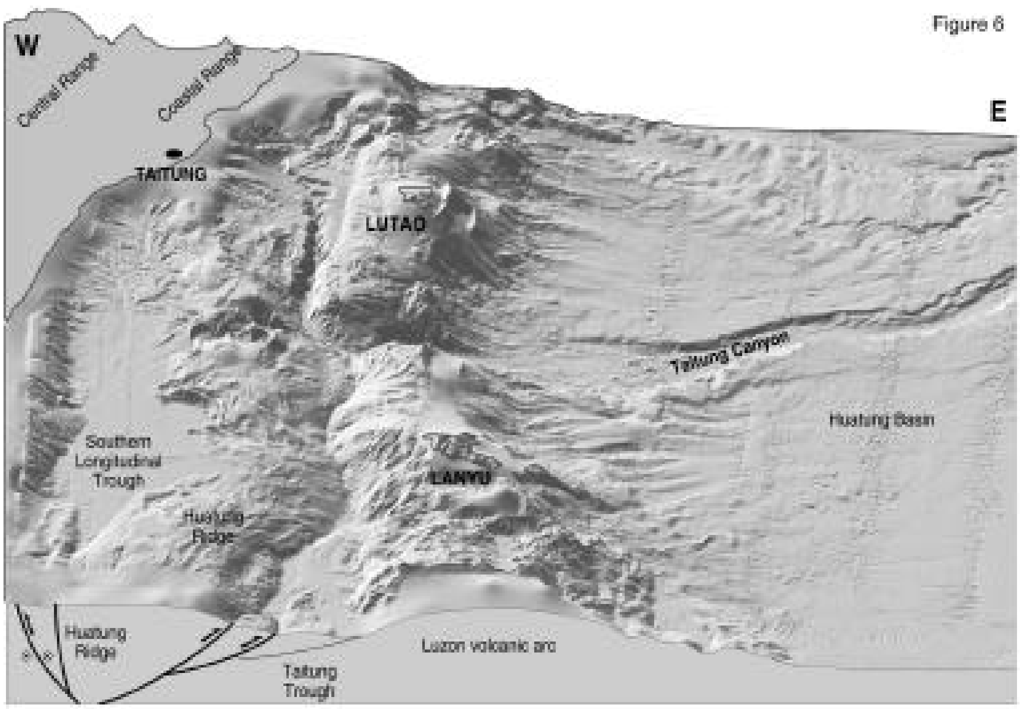


Figure 6: Shaded hill relief (perspective view) of the southeastern area showing the main morphostructural features (looking north).

Migrated 6-channel, seismic reflection profiles, acquired during the MW9006 cruise of the R/V Moana Wave in 1990, across the SLT 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-dipping east-vergent thrusts have been imaged from E-W seismic lines [Lundberg et al., 1997].

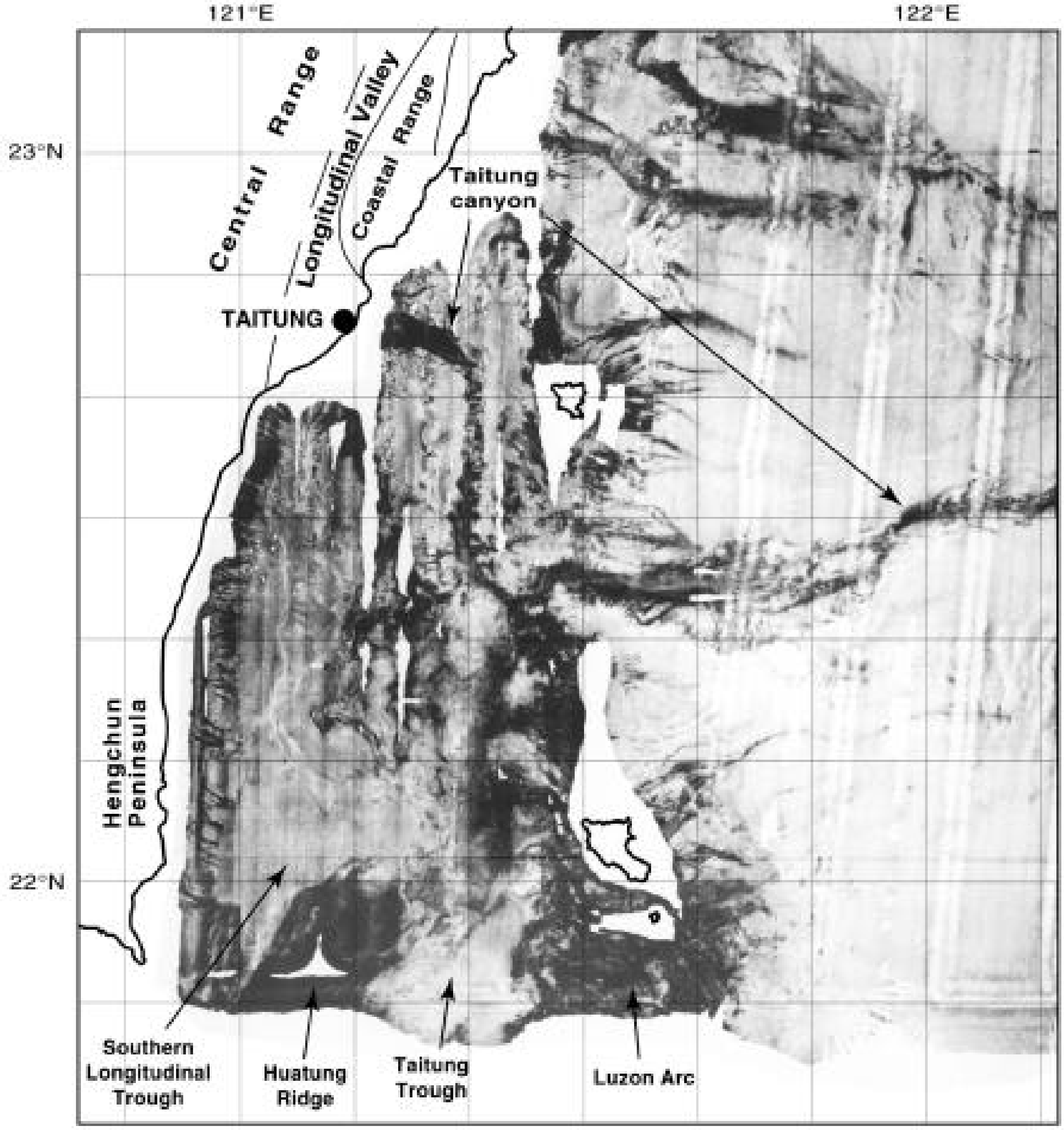


Figure 7: Side-scan sonar imagery of the study area. Note the strong reflectivity (black) of the Taitung Canyon floor, top of Huatung Ridge and Luzon volcanic arc, and the low reflectivity of the small channels of the SLT and of the southeastern steep slope of the Huatung Ridge.

Figures 8, 9 and 10, represent time migrated 6-channel seismic lines ACT - 49 - 48 - 47 recorded along the SLT (see Figure 2 for location). These three parallel N-S lines illustrate the complex structure of the trough.

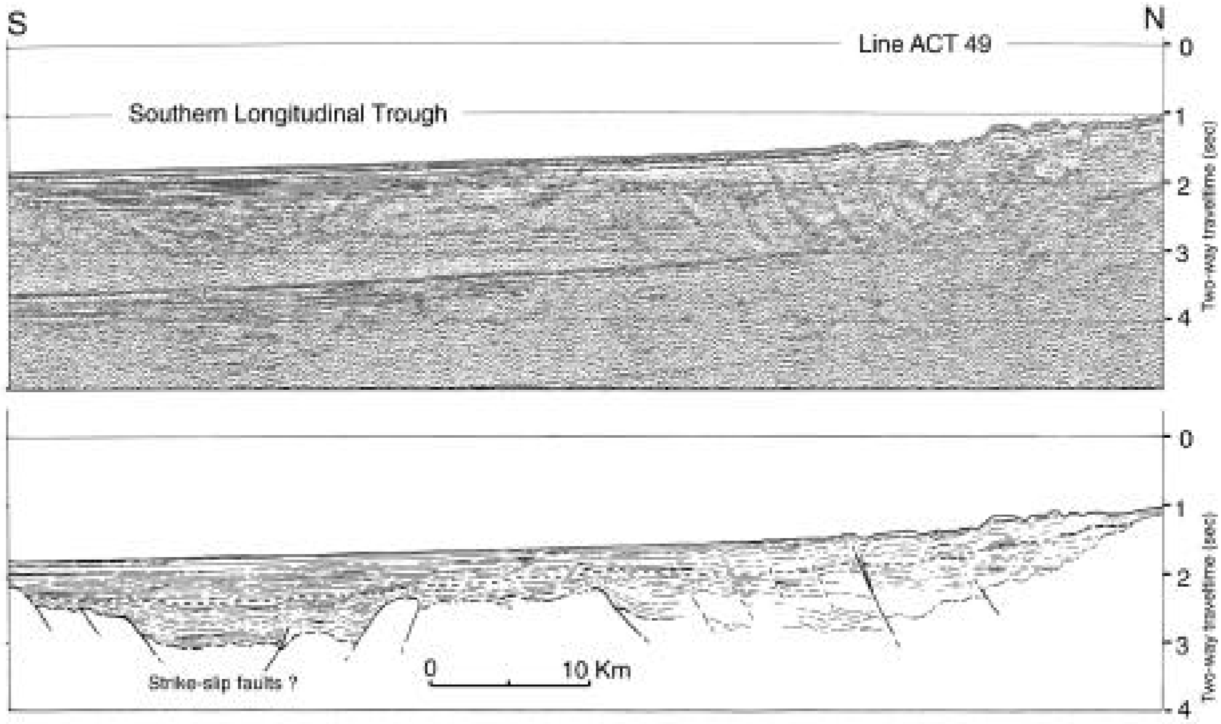


Figure 8: North-south seismic profile across the eastern part of the Southern Longitudinal Trough (SLT). a) Migrated 6 channel profile, b) line drawing showing the main geologic features.

The line ACT 49 (Figure 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.

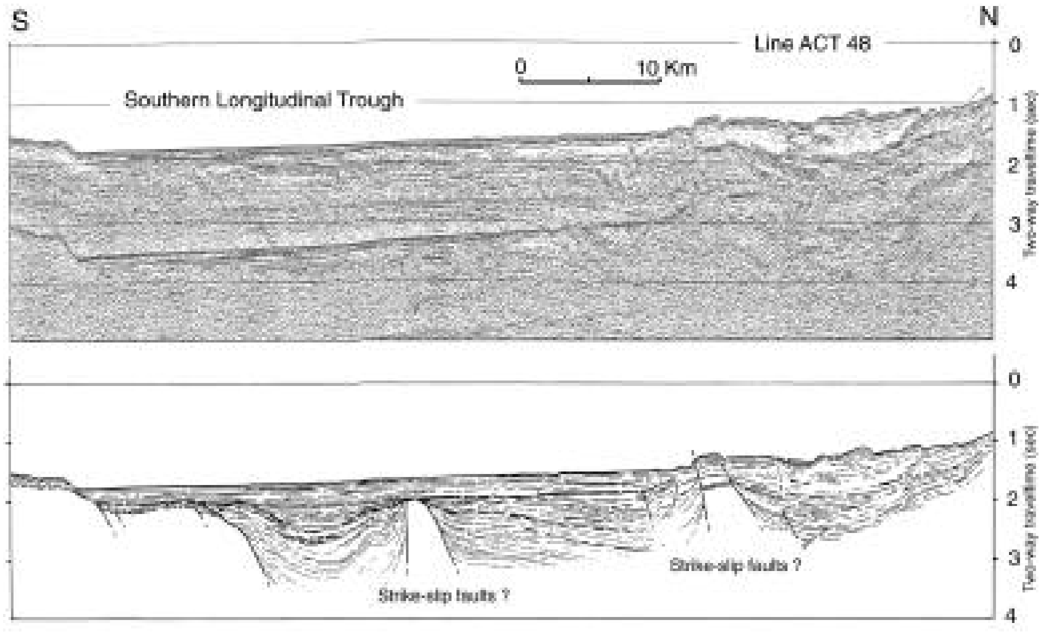
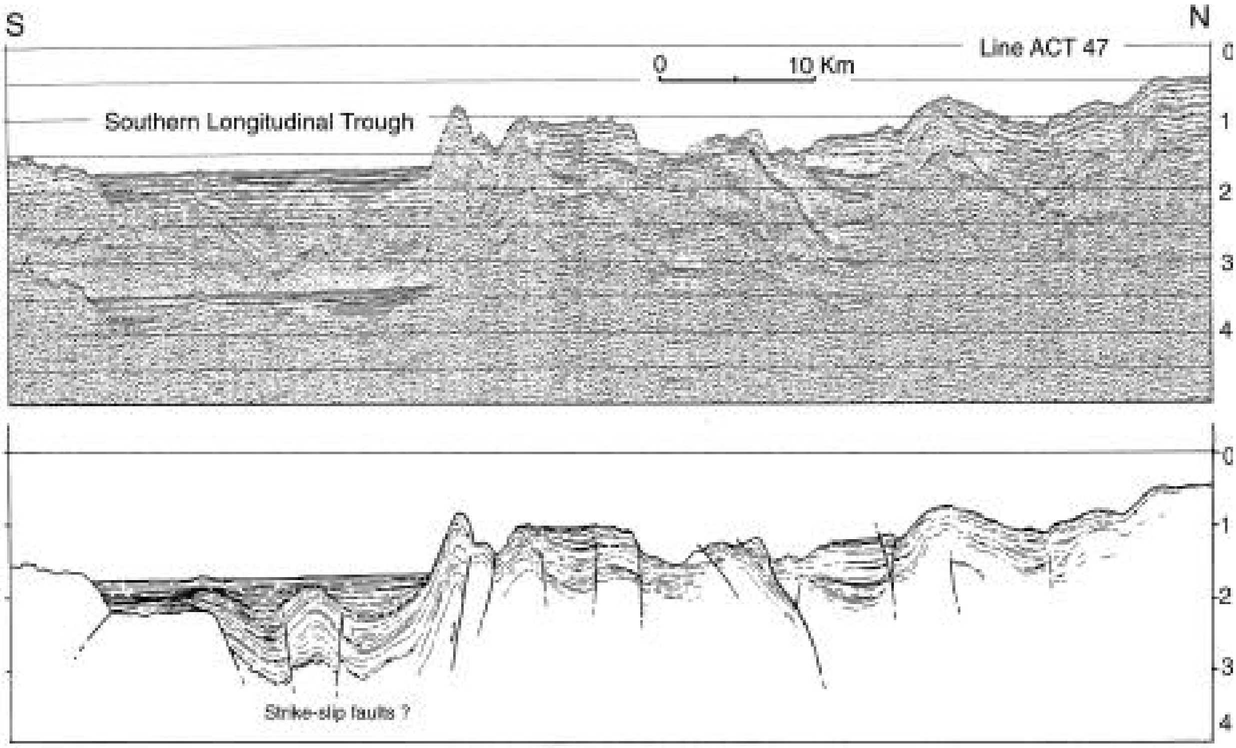


Figure 9: North-south seismic profile across the central part of the SLT. a) Migrated 6 channel profile, b) line drawing showing the main geologic features.

On the line ACT 48 (Figure 9), located on the median part of the trough, the thickness of the younger series 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 3 minor troughs: a southern one, suffering folding in 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 (Figure 10) crosses the eastern part of the SLT and shows that the undeformed sequences in the upper part of the basin exist only in the southern trough (see also figure 4). These sequences lie unconformably on top of older, folded and faulted sequences of the former trough. In the northern domain, the lower sequences have undergone complex deformation involving thrusting.

Our observations suggest that the SLT was developed in a complex tectonic setting during at least two different stages. First, an early stage of basin development in an area of active shortening. The shape of thrusts are interpreted as positive flower structures, and the orientation of the folds oblique to the N-S 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 PHS. A more recent second stage occurred during which the sediments were deposited unconformably on top of the formerly deformed. This later stage occurred after the main region of deformation migrated eastward towards the Huatung Ridge.

After correlation of the strata on both E-W and N-S lines at intersecting points, we observe that the "nearly flat-lying" uppermost strata along E-W transects are gently folded along axes oblique to the N-S trend of the basin (Figure 6) with strata locally dipping 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 presently characterized by west-vergent thrusting [e.g. Angelier et al., 1997], we expected before the cruise to find the same active deformation in the SLT. Despite the morphological continuity between the Longitudinal Valley onland and the offshore trough, the most surprising observation was the absence of any sign which could reveal the activity of west-vergent reverse faults in the SLT [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° east-dipping structural slope), (2) the orogenic N-S elongated sedimentary basin follows the N 30°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 antiformal structures of the Huatung Ridge, not by equivalents of the west-verging thrusts of the Coastal Range.

The Huatung Ridge. The above 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 conclude that it consists mainly of a sedimentary mass. Reed et al. [1992] suggested that the deformed forearc basin forms an important constituant 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 melange formed during the arc-continent collision [e.g., Page and Suppe, 1981; Huang et al., 1992].

The ridge is not continuous. North of 22°02'N, it trends N-S, is 20 to 30 km wide and it reaches 600 m with respect to the adjacent SLT floor (Figure 4). South of 22°02'N, it trends N20°E, 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 (Figure 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 latitude 22°10'N and increases to 2400 m to the north and to 2100 m to the south. The average slope is 10° but reaches 20° in the northern part of the ridge (Figure 4). South of the study area, the E-W ACT 53 seismic profile (Figure 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 (Stéphan, personal communication, 1996) [Pelletier, 1985] and later during the R/V Moana MW9006 cruise in 1990 [Lundberg et al., 1997].

South of 21°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 (Figure 5, section 1) [Reed et al., 1992; see also Larroque et al., 1995, for the mechanisms of basin development]. At 22°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 3,000 m toward a pass, 2,200 m deep, at 22°10'N (Figures 1 and 4). This morphology, together with the westward tilting of the overlying strata of the SLT, show that the Huatung Ridge is thrusting over the Luzon volcanic arc at least between 22°N and 22°25'N.

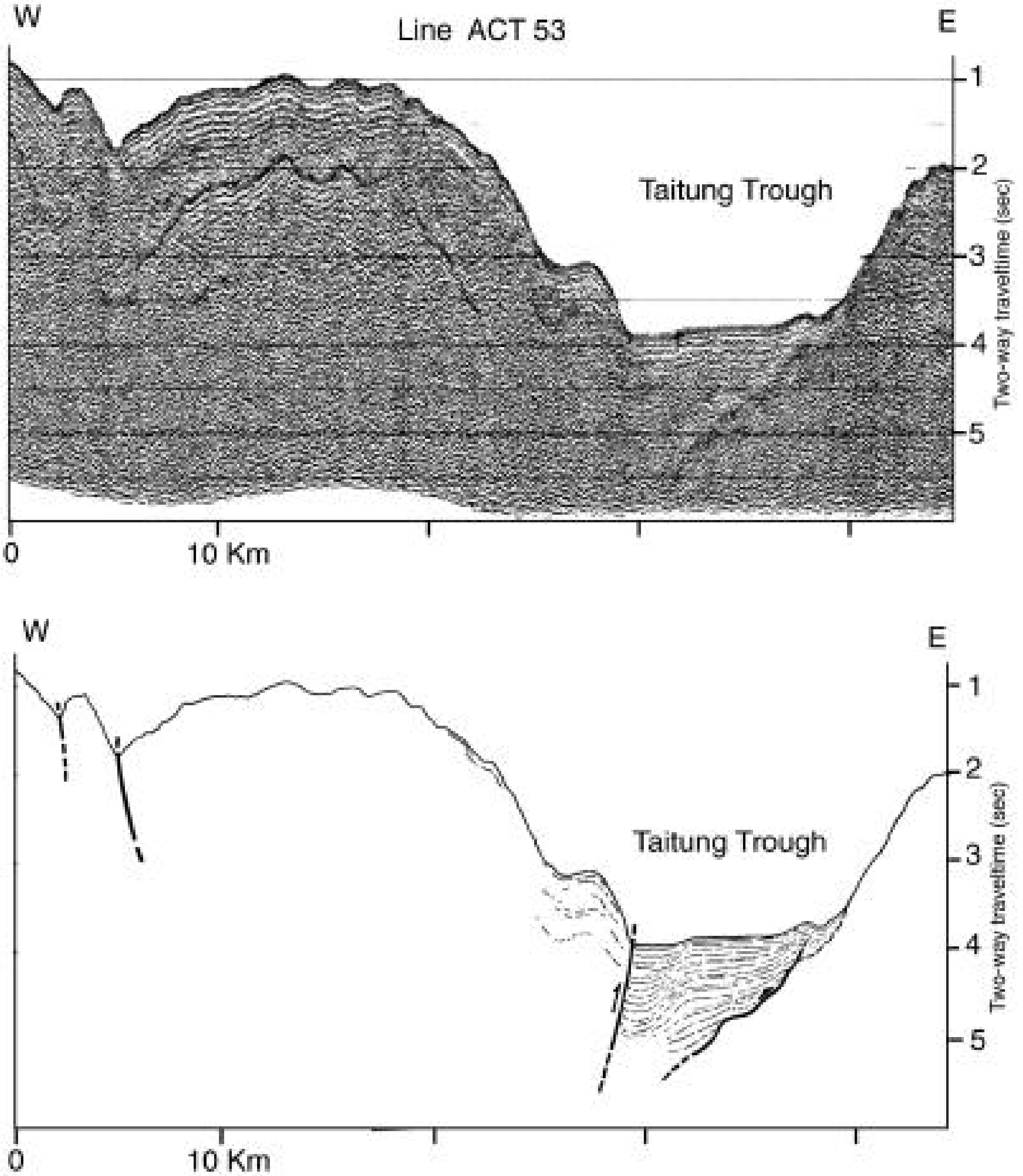


Figure 11: East-west seismic profile south of the study area. a) Migrated 6 channel profile, b) line drawing showing the main geologic features.

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°20'N (also described in Lundberg et al. [1997]). North of 22°25'N, the Huatung Ridge widens and is cut by the head of the Taitung Canyon which extends southward to 22°25'N where it turns east and crosses the volcanic edifice to join the Huatung Basin to the east. The N-S 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 Lutao Island. The thick sequence of sediments in this basin remain tectonically undisturbed as revealed by E-W reflection seismic lines [Huang et al., 1992] and N-S seismic profiles (this study). At about 22°22'N, a sinuous canyon incises the Huatung Ridge and joins the E-W trending segment of the Taitung Canyon (Figure 12).

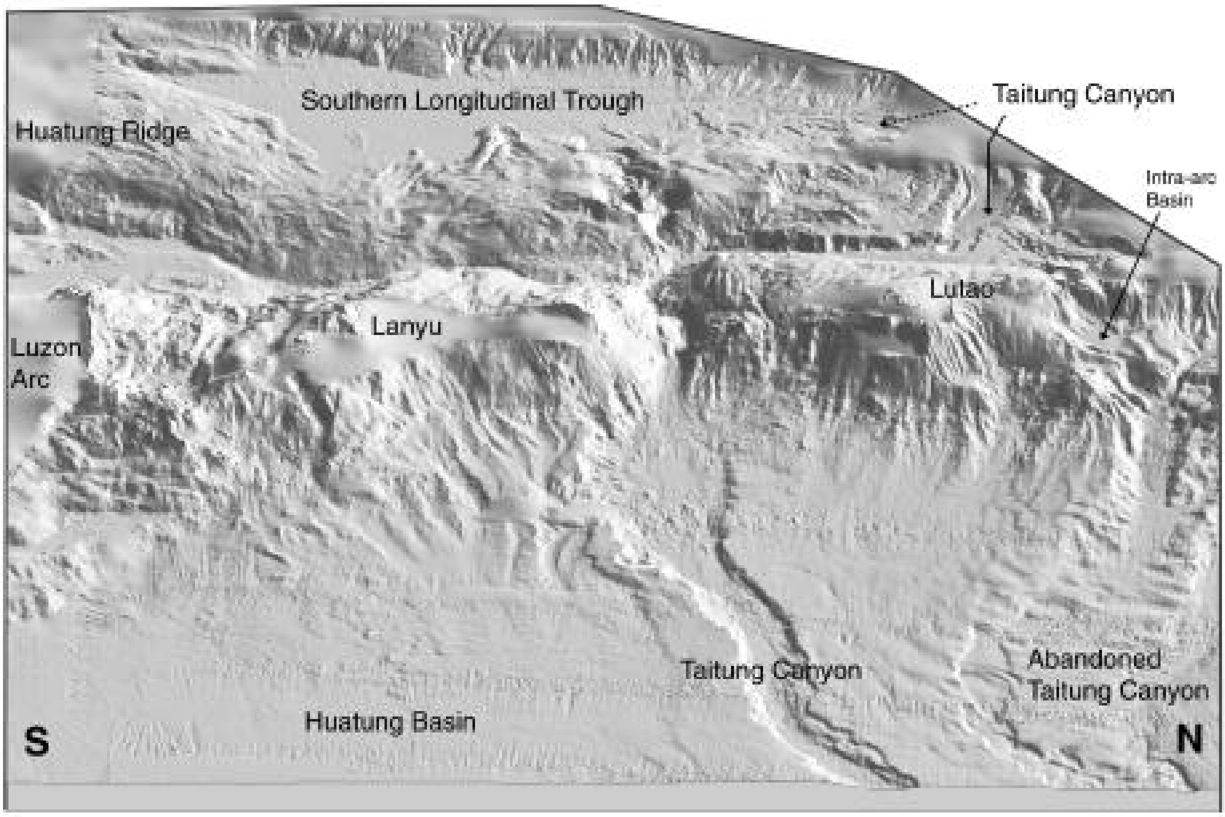


Figure 12: Shaded hill relief (Perspective view) of the southern part of the study area (looking west).

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 SLT and then crossed the ridge and the volcanic arc to join the Huatung Basin. It seems that due to the rapid growth of the Huatung Ridge and increasing thrusting to the east over the arc, the paleo Taitung Canyon was progressively abandoned or became less efficient. Its new bed was uplifted, resulting in the N-S canyon, presently crossing through the Taitung Basin, deeply incising the strata.

The ACT data, show that the shortening between the Luzon Arc (Lutao and Lanyu islands) and the Hengchun Peninsula of Taiwan is mainly absorbed along the west-dipping thrust beneath the Huatung Ridge, and partially 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 (Lutao 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. Onland, two main tectonic units are characterized by active deformation. The boundary between the southern and northern unit is marked by the northwest vergent Chimei Fault (Figure 4).

Offshore, east of the Coastal Range, the slope is actively deforming. Minor NW-SE trending strike-slip faults (probably left-lateral), east-verging thrusts and NNE-SSW folds characterize the deformation (Figures 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 Figure 13). It has been interpreted from the seismic line EW 9509-05 (Figure 14) [Liu et al., 1998], slightly oblique to the scarp, as caused by E-SE-vergent reverse faults. North-south ACT seismic profiles show that most of the offshore slope is covered by sediments, that could be derived from the 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.

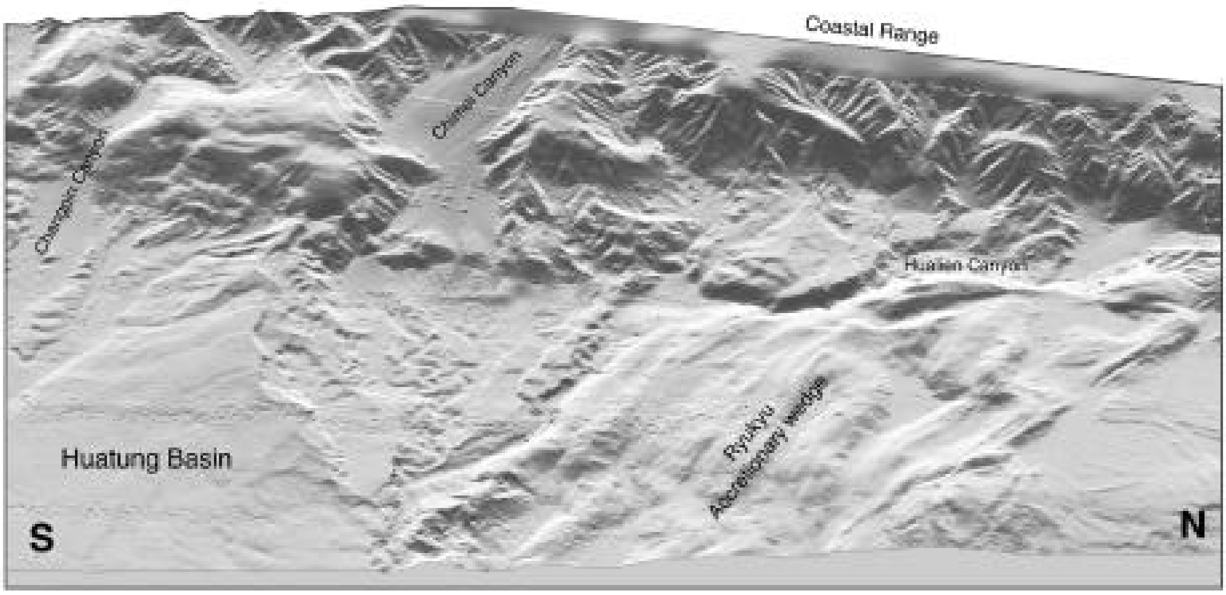


Figure 13: Shaded hill relief (Perspective view) of the eastward dipping slope offshore of the Coastal Range, viewed from the east. It shows the prominent N-S trending fault scarp cutting the base of the slope.

The submarine Hualien Canyon flows roughly N-S through the Ryukyu accretionary wedge and follows the trench where it runs eastward joining the Taitung Canyon close to the Gagua Ridge (Figure 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 trench. Several other minor canyons coming from the eastern flank of the Coastal Range mountains flow downslope towards the Huatung Basin (Figure 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 occur offshore, through west-dipping thrusts (calculated using geodetic data [Yu et al., 1997]).

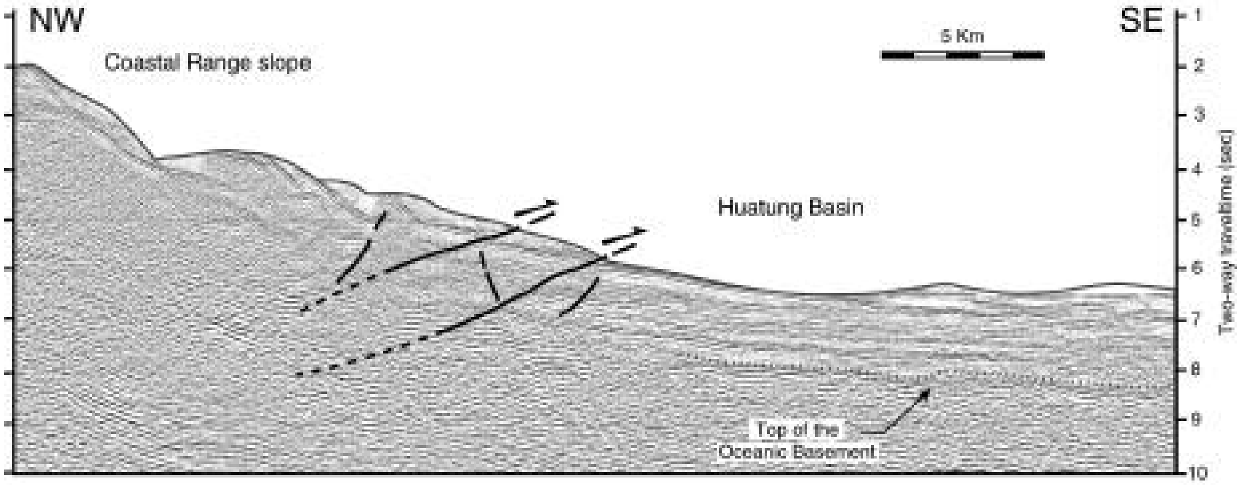


Figure 14: Northwest-Southeast seismic profile showing the east vergent thrust cutting the base of the slope. Ewing data, 160 channel profile.

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 portion 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 (Figure 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 PHS 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 (Figure 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 presently 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 E-W trending canyons (Chimei Canyon for example) also cut the east dipping slope of the island, developing deep-sea fans of gravelous sediments and transporting detritus far towards the east in the Ryukyu Trench (Figure 13). These observations suggest that the general tectonic and sedimentologic environment have 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 (Figure 4). A NE-SW-trending, curved fault zone characterized by a 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 N-S oriented seismic profiles acquired during the ACT cruise show evidence of northwest-dipping thrusts in this area. For example, line ACT 36 (Figure 15), shows a southeast-verging thrust, which offsets recent sediments of a small ponded basin lying on the back side of a submarine volcano, north of Lutao Island (Figure 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 (Figure 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.

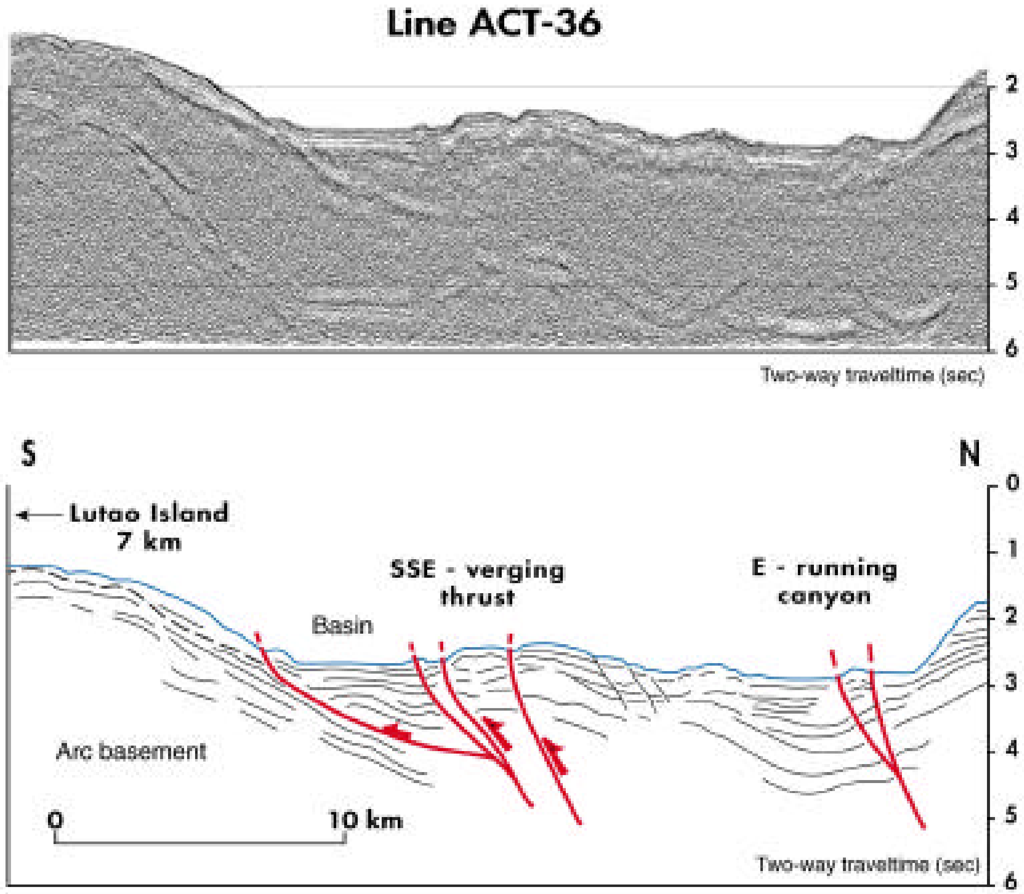


Figure 15: North-south seismic profile showing the transfer zone of deformation which develops at the south eastern tip of the Coastal Range. a) Migrated 6 channel profile, b) line drawing showing the main geologic features.

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 ± 10 km/Ma from north to south. This is in good agreement with the existence of a major transfer zone of deformation at the latitude of Taitung, which coincides with the 1,000 m of difference in elevation between the Longitudinal Valley and the SLT (Figure 4), the clockwise rotation of the Coastal Range tectonic units and change in trend of the island arc (Figure 3). Today, this transfer zone may account for the reversal of thrusting polarity, which occurs near Taitung, by allowing the simultaneous activity of both west vergent thrusting of the Coastal Range and eastward backthrusting of the Huatung Ridge onto the arc (Figure 4).

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. 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 its southern part. 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 (Figure 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.

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: i) The volcanic arc was poorly developed or missing in this region of the Philippine Sea Plate or ii) The frontal part of the arc was subducted during an earlier stage of the collision.

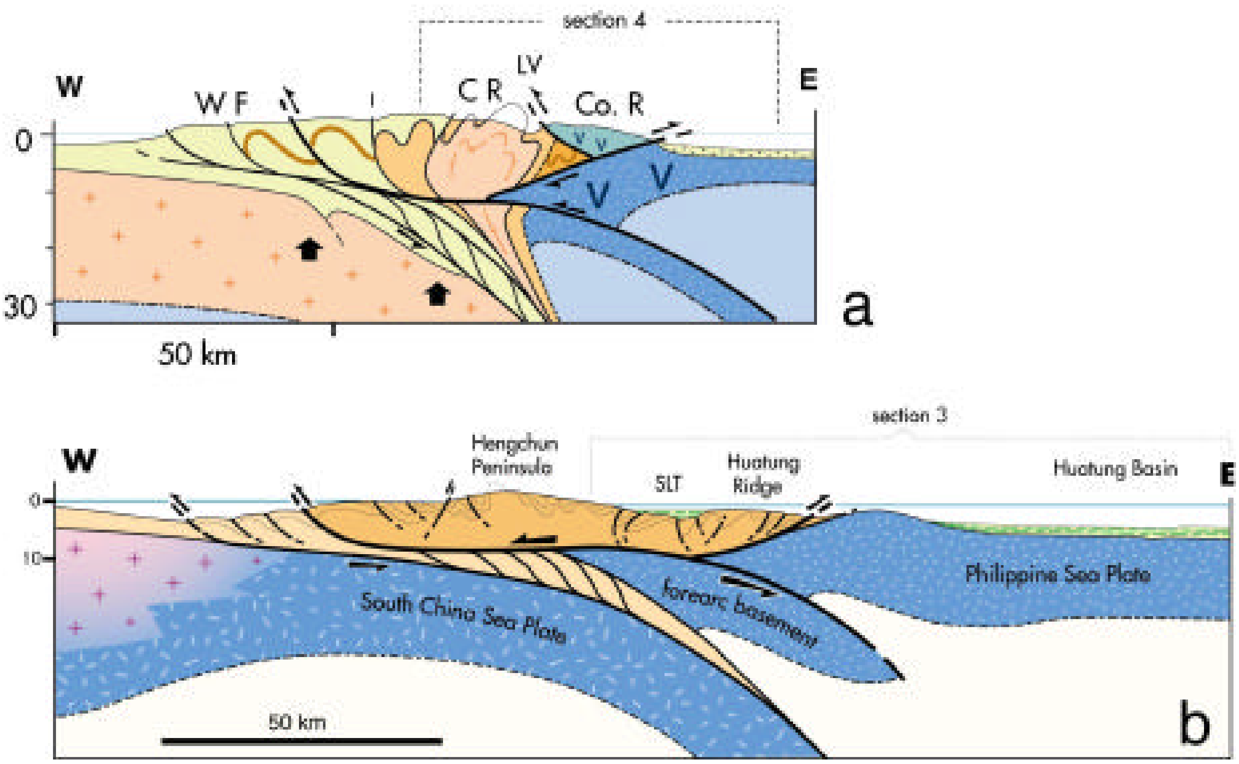


Figure 16: Interpretative geologic cross sections a) south of the collision zone and b) at the latitude of the Coastal Range.

Figure 16 presents two interpretative, lithospheric scale cross sections in the collision zone which account for our observations. The first (Figure 16a) is located at the latitude of the Hengchun Peninsula, the second (Figure 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 underthrusted beneath the Coastal Range within a distance between 22°50'N and 24°10'N (cross-section 4 of Figure 5 and Figure16a). The detailed mechanism remains somewhat enigmatic, because a sliver of about 90±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 obtain 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 forearc beneath the arc. This process would allow enough time to exhume 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, underplating at depth beneath the Central Range, and erosion. The last (present) event being the westward thrusting of the Coastal Range on the Central Range.

In the southern domain (south of 22°40'N) the collision process is less evolved and the continental margin of China is not yet subducting beneath the PHS 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 could result from uplift above the underplating of subducting 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. The arguments favoring this hypothesis are : south of 22°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 SLT collisional basin and 2) out of sequence thrusting in the wedge which 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 mélange was deposited earlier, but further to the north. The Huatung Ridge has been shown to be made in part by folded and faulted sediments of the basin. In such a case, they represent equivalents of the onland Lichi mélange, which is interpreted as the most recent suture zone between the Luzon Arc and the Eurasia margin in Taiwan. This second "suture" would mark the recent jump of basement underthrusting to the east in the forearc. The age of the mélange 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 toward the south, because it consists of sediments that have been recently deposited in the SLT, south of the Longitudinal Valley. The Longitudinal Valley, whose morphology is well-expressed onland, has no similar expression offshore either to the north or to the south.

Because a 50-to-80 km wide segment of the forearc basement (from magnetism) [Liu et al., 1992] has disappeared from section a to b (Figure 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 on Figure 16). This interpretation, based on the geometry of the system, implies that the western side of a paleo-Longitudinal Valley fault (presently 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; Chemenda et al., 2001; Tang et al., this issue] who applied the models to Taiwan. Exhumation of the Central Range, associated with synorogenic surficial extension and apparent normal faulting along the eastern side of the Central 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°N results from the simple evolution of a stage at 22°N, which in turn results from the increasing compression of a stage at 21°N. Because of the obliquity of the plate convergence and the geometry of the ocean-continent transition in the Eurasia plate, the 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., 1997]. The western termination of the Ryukyu accretionary wedge, and the complex area which 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 describes 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 been omitted, thus, the growth of the collision thrust wedge is only suggested on the Eurasia plate. Figure 18 describes the same stages of the tectonic evolution along a reference E-W cross section located at the same latitude as the present Central Range of Taiwan and shows the main tectonic units involved in the collision.

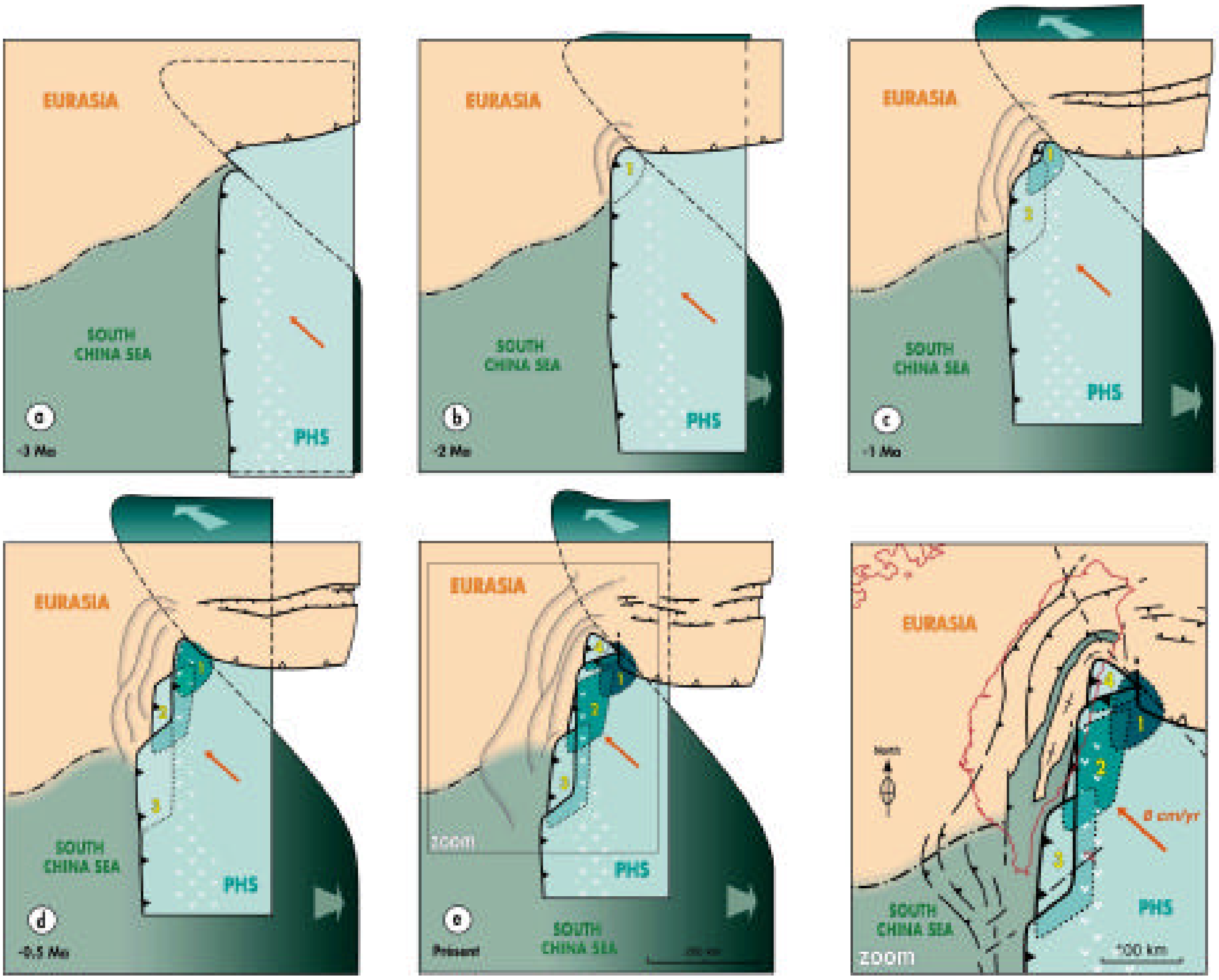


Figure 17: 3D Geodynamic model of the Taiwan orogen. a, b, c, d, e, show the different stages since 3 ma (see explanation in the text). Only the plate boundaries and the limits of the basement thrusts in the PHS are shown, thrust wedge sediments have been removed.

First stage. It shows the oblique subduction of the PHS beneath Eurasia to the north and the subduction of the oceanic lithosphere of the SCS under the Luzon arc to the south (Figure 17a). At that time, a major transform fault connected the two oppositely verging subduction zones. The section of Figure 18a shows the beginning of continental margin subduction beneath the Manila accretionary wedge.

Second stage. During the second stage (Figure 17b), the northwestern corner of the PHS deforms the continental margin of China, which begins to subduct inducing a stress increase in the forearc lithosphere of the PHS. Figure18b 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 PHS, which forms a backstop. Increasing stress in the PHS 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.

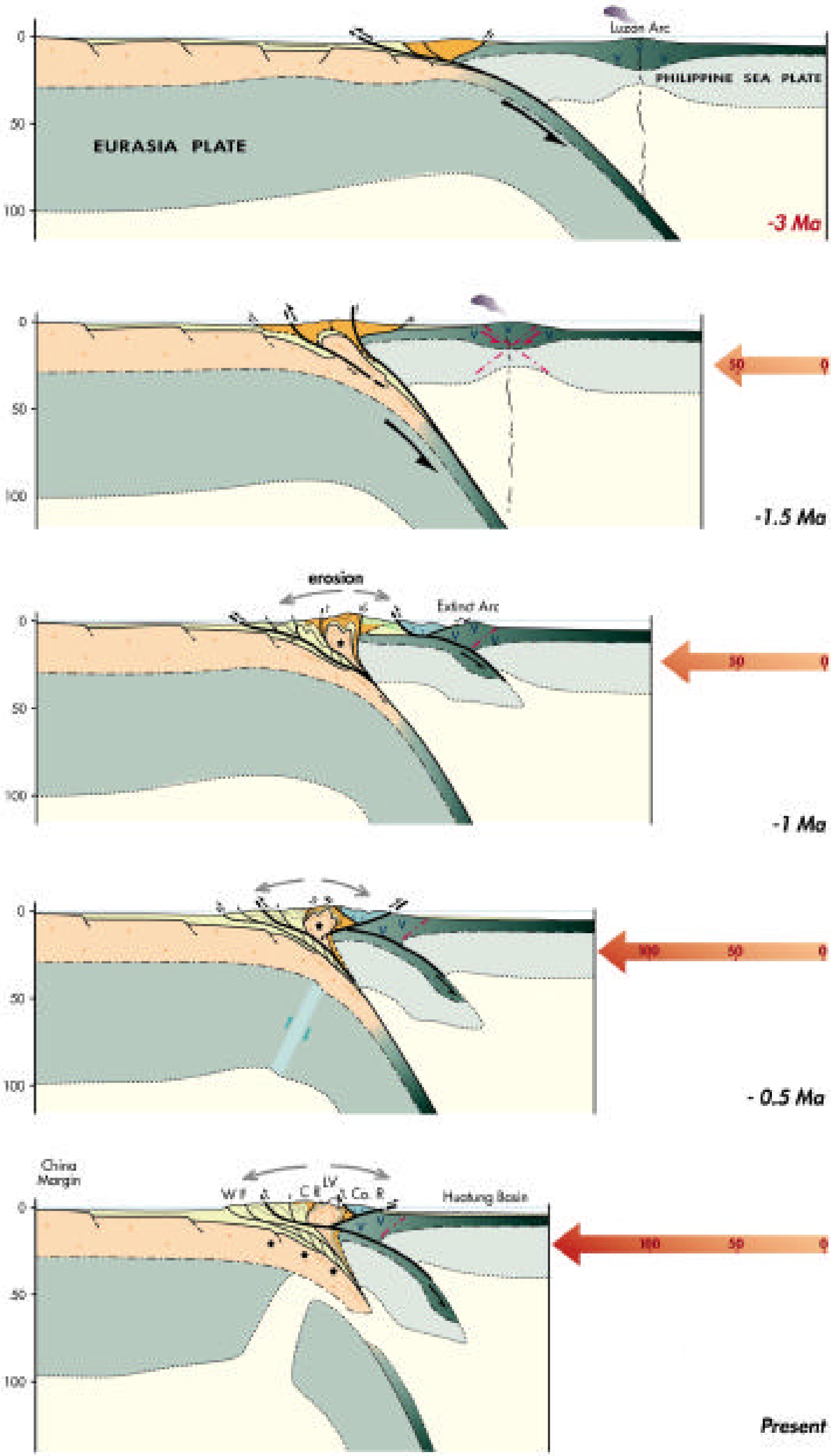


Figure 18: Tectonic evolutionary model of the Taiwan orogen since the beginning of the collision (see explanation in the text). The sections are correctly balanced.

Third stage. It is marked (Figure 17c) by the thrusting of a slice of the forearc lithosphere (unit 1 of the Figure) beneath the arc. Collision-related deformation migrates to the south, involving stress increase in a new domain of the PHS. Section c of Figure 18 shows the different processes that occur during this complex evolutionary stage. To the east, the volcanic activity of the arc is stopped by the subduction of the forearc sliver, which cuts the magma source. West of the extinct arc, a complex collisional basin develops, mainly filled by sediments eroded from the Taiwan mountain belt. A new thrust wedge develops, against the arc edifice, composed of volcaniclastic 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 involves 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 are progressively exhumed and rise through the overlying rocks of the old oceanic wedge due to the combined effects of erosion of the internal domain of the wedge and probable underplating at depth favoring uplift. The vertical motion of metamorphic rocks occurs against the subverticalsurface marking the western extent of the backstop formed by the forearc lithosphere. The western boundary of the Central Range will be 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 melanges) resting on top of it, are deeply eroded becoming the source for the olistostromal melanges presently included in the Lichi formation. Most of these sediments are deposited in collisional basins during shortening of the forearc domain and have been later involved in thrusting.

Fourth stage. Figure 17d shows the southward migration of deformation and the subduction of a second slice of the forearc lithosphere (unit 2), whereas further south, another domain (unit 3 of the Figure 17) of forearc lithosphere is subjected to a stress increase. Foreland deformation develops to the west in the Taiwan strait. Offscraped remnants of the forearc domain including forearc- and intra-arc basin sediments are tectonically mixed with sediments of former collisional basins. A new mechanism allows exhumation to continue. The former assymetrical mechanism of wedge growth by forward thrusting [e.g., Malavieille, 1984] is replaced by a more symmetrical evolution with significant backthrusting (Figure 18d). Uplift occurs now due to the conjugate effects of west-vergent forward out of sequence thrusting, and east-vergent backthrusting. The forearc domain has been shortened significantly at this stage.

Present situation. It is shown on the Figure 17e. A third unit of forearc lithosphere (unit 3) begins subducting to the south, 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 west vergent, out of sequence thrust (Figure 18e). The main tectonic features of Taiwan are presented on the Figure 17f.

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

i) First, increasing stress in the northernmost domain of collision induces the propagation of a NW-SE trending transform-tear fault which bounds the Ryukyu slab to the southwest. Failure in the oceanic lithosphere results in the detachment of a fourth tectonic unit (unit 4 of Figure 17e). In this domain, most of the convergence occurs southeast of this unit probably on west vergent blind thrusts merging below the eastermost part of the Ryukyu accretionary wedge and joining the basal décollement in the Ryukyu trench system. This hypothesis is described in the Figure 17e.

ii) As proposed by Chemenda et al., [1997], after removal of the forearc crust, due to the indentation by the arc lithosphere, a major east vergent thrust develops cutting through the continental lithosphere of the China margin (see figure 12d, p. 267 and figure 13, p. 268 in Chemenda et al. [1997]). This process results in the development of a new subduction zone which propagates southward.

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

Geophysical constraints. Numerous geophysical studies help to constrain 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 ; Rau and Wu, 1998 ; Wu et al., 1997 ; Kao et al., 1998 ; Cheng et al., 1998; Cheng et al., this volume].

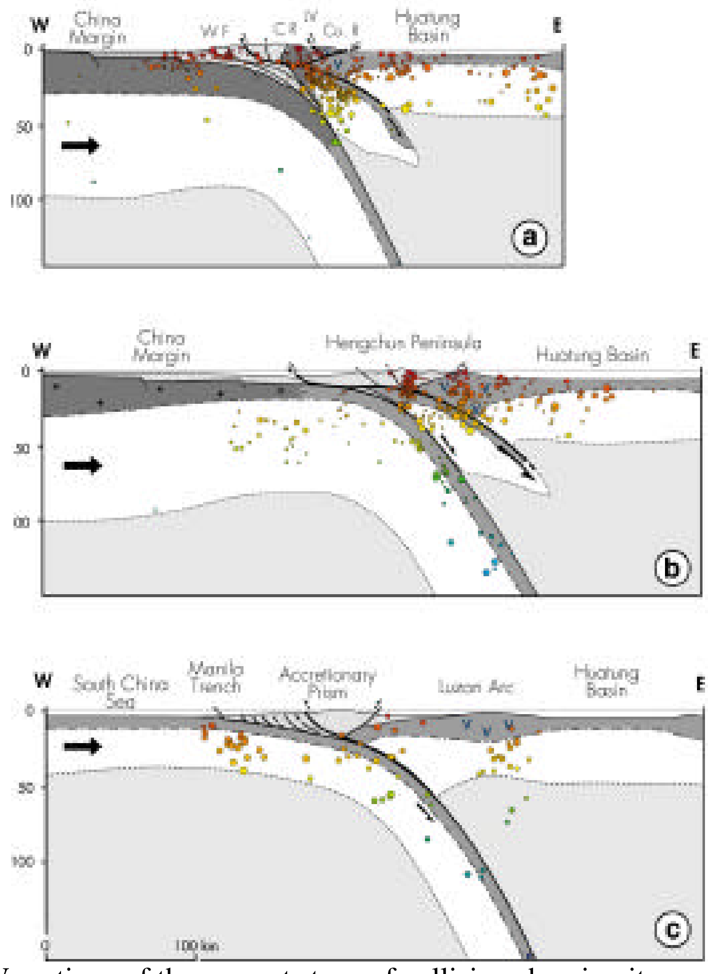


Figure 19: E-W sections of the present stage of collision showing its evolution in space from the south to the north of the orogen (for location see Figure 1). Seismicity data from global (Engdahl et al., 1998) and regional networks (Wu et al., 1997; Cheng et al., 1998) have been

projected onto the three sections. a) section at 23°N, across the Taiwan mountains, b) section at 22°20'N, across the Hengchun Peninsula and c) section at 21°N.

The last Figure 19 shows three interpretative sections of the present stage of collision process and its evolution in space from the south to the north 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.

In the southern tectonic domain, two E dipping bands of Seismicity can be distinguished (see central section of Figure 19b): a broader, steeply dipping (50-60°) band to the west representing the plate boundary and subducting lithosphere of the Chinese margin, and a narrower, more shallowly dipping band beneath the arc at 20-40 km depth. The latter corresponds well to the 20° E dipping underthrusting focal plane from 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 zone of high velocity anomaly in the middle- to lower-crust, which could correspond to the underthrusting of forearc crust.

SUMMARY AND CONCLUSIONS

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 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 (LV) disappears offshore to the south, below the Southern Longitudinal Trough (SLT), a collisional basin filled with recent orogenic sediments laying unconformably on deformed and folded strata of the former forearc domain. Transpressive deformation plays an important role during the development of the SLT. Present deformation has jumped to the east and it is characterized by the growth of a sedimentary ridge (the Huatung ridge, rear portion 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 an active eastward thrusting of parts of the arc (volcanic edifices and intra-arc or forearc sediments) 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 accomodates the differential motion and rotation of the northern and southern tectonic units.

Relationship of Coastal Range and offshore structure along eastern Taiwan to distribution of canyons and deformation offshore Hualien and Ryukyu trench are also described.

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” portion of forearc crust in the region of collision and the tectonic evolution of the Taiwan orogen.

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